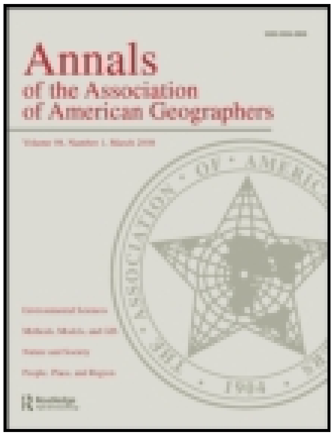

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Justin C. Stout [a b] , Patrick Belmont [b] , Shawn P. Schottler [c] & Jane K. Willenbring [d]
[a] Department of Resource Management and Geography , University of Melbourne
[b] Department of Watershed Sciences , Utah State University
[c] St. Croix Watershed Research Station
[d] Department of Earth and Environmental Science , University of Pennsylvania
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Identifying Sediment Sources and Sinks in the Root River, Southeastern Minnesota

Justin C. Stout,*,† Patrick Belmont,† Shawn P. Schottler,‡ and Jane K. Willenbring§

*Department of Resource Management and Geography, University of Melbourne
†Department of Watershed Sciences, Utah State University
‡St. Croix Watershed Research Station
§Department of Earth and Environmental Science, University of Pennsylvania

Excessive loading of fine sediment is a prominent cause of river impairment, not only due to direct effects on biota and habitat but because sediment is often laden with excess nutrients, metals, and toxic substances. Determining the sources and transport pathways of sediment has proven challenging. The Root River watershed in southeastern Minnesota was listed under section 303d of the U.S. Clean Water Act as having forty-three impaired reaches, raising these questions: Where is the fine sediment coming from? What proportions of the sediment are from uplands versus near-channel erosion? How much of the excess sediment loading is caused by modern land use and water management versus the legacy of past land use? Managing fine sediment at the watershed scale requires that we identify potential sources and sinks throughout the watershed, measure source contributions, and understand transport pathways of fine sediment. Here we utilize sediment fingerprinting techniques involving long- and short-lived radionuclide tracers, specifically beryllium-10 (^{10}Be), excess lead-210 ($^{210}Pb_{ex}$), and cesium-137 (^{137}Cs), in combination with other supporting data sets to address the preceding questions. We document a shift in hydrologic regime and that sediment fluxes are sensitive to both magnitude and sequence of flood events. Geomorphic analysis indicates that many river reaches have accessible near-channel sources that contribute the dominant proportion of the washload flux in subwatersheds. Lastly, geochemical tracer analyses of floodplains and hillslope soils indicate that historic erosion has been variable across the landscape and the majority of suspended sediment in the river today is sourced from floodplains and terraces. *Key Words: floodplain, radiogenic nuclides, sediment fingerprinting, terraces.*

承载过量的细粒沉积物, 是导致河流受损的重要原因, 不仅因为动植物及其栖地所造成的直接影响, 亦因为沉积物经常充斥着过多的养分、金属与有毒物质。确认沉积物的来源与运送途径被証实是相当困难的。明尼苏达东南方的根河流域, 拥有四十三个受损的河段, 因而名列美国洁淨水资源法案的 303d 受损水体名单之上, 并直指下列问题: 这些细微沉积物从何而来? 这些沉积物来自上游与来自近沟槽侵蚀的比率为何? 过多的沉积物承载量中, 由现代土地使用及水资源管理相对于由过去土地使用的遗续所造成的比率为何? 为了管理流域尺度的细粒沉积物, 我们需要指认整个流域中潜在的来源与汇集点、测量各源头的影响, 并了解细微沉积物的输送通道。我们在此运用包含长、短寿命放射性核素示踪的沉积物鑑别技术, 特别是鈹-10 (^{10}Be) 、过量的铅-210 ($^{210}Pb_{ex}$), 以及铯-137 (^{137}Cs), 并结合其他支持性的数据集, 用以回应上述问题。我们记录水资源情势的转变, 其中沉积物流同时受到洪水事件的级别与连续性所影响。地形学的分析显示, 许多河流的河段拥有造成子流域的冲洗载流中具支配性比例的可及性近沟槽来源。最后, 洪泛平原与坡地土壤的地理化学追踪分析指出, 地景中的历史侵蚀是多变的, 而目前河流中多数的悬浮沉积物则是源自于洪泛平原及台地。 *关键词: 洪泛平原, 放射成因核素, 沉积鑑别, 台地。*

La carga excesiva de sedimento fino es una de las causas más importantes de los problemas de un río, no solamente por los efectos directos sobre la biota y el habitat sino porque a menudo el sedimento va sobrecargado de nutrientes, metales y sustancias tóxicas. Determinar las fuentes y las rutas de transporte del sedimento ha resultado problemático. La cuenca del río Root, en el sudeste de Minnesota, fue registrada en la sección 303d de la Ley de Aguas Limpias de los EE.UU., con una cuenta de cuarenta y tres inconvenientes, generando tres interrogantes: ¿De dónde proviene el sedimento fino? ¿Qué proporción de los sedimentos proviene de las tierras altas frente a la generada por erosión cercana al cauce? ¿Qué tanto de la carga excesiva de sedimento es causada por usos modernos del suelo y manejo de las aguas frente al legado de usos pretéritos? El manejo del sedimento fino a la escala de cuenca hidrográfica exige la identificación de fuente potenciales y sumideros en toda la cuenca, la medición de los aportes por cada fuente y comprensión de las rutas de transporte del sedimento fino. En este caso utilizamos técnicas de identificación de las huellas del sedimento en las que se involucran rastreadores

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de radionucleidos de vida larga y corta, específicamente berilio-10 (^{10}Be), el isótopo de plomo-210 ($^{210}PB_{ex}$) y cesio-137 (^{137}Cs), combinados con otros conjuntos de datos de apoyo para abocar las preguntas enunciadas. Documentamos la existencia de un desvío en el régimen hidrológico y la idea de que los flujos de sedimento son sensibles tanto a la magnitud como a la secuencia de los eventos de inundación. El análisis geomórfico indica que muchas de las crecientes de los ríos dependen de fuentes cercanas accesibles al cauce, que aportan la proporción dominante de la carga de escorrentía a manera de subcuencas hidrográficas. Por último, los análisis de rastreadores geoquímicos en las planicies de inundación y en los suelos de las laderas indican que la erosión histórica ha estado variando a través del paisaje y que la mayoría del sedimento en suspensión del río en la actualidad se nutre desde las planicies de inundación y las terrazas. *Palabras clave: planicie de inundación, nucleidos radiogénicos, identificación de la huella del sedimento, terrazas.*

Fine sediment, including sand, silt, and clay (grain sizes < 2 mm), dominates the material flux of many rivers and plays a key role in nutrient transport, channel morphology, light penetration, and food-web dynamics (Martin and Meybeck 1979; Macklin, Hudson-Edwards, and Dawson 1997; Palmer et al. 2000; Naden 2010). The U.S. Environmental Protection Agency (EPA) lists sediment among the most important pollutants in U.S. waterways (U.S. EPA 2012), yet we lack rigorous means to differentiate between natural and anthropogenic sediment loads, which vary by several orders of magnitude in time and space. Globally, humans have significantly increased terrestrial erosion, and a combination of anthropogenic and natural sediment sinks have dramatically reduced sediment delivery downstream through river networks (Trimble 1999; Syvitski et al. 2005; Montgomery 2007). An improved understanding of sediment routing that accounts for storage and resuspension is critical for developing reliable predictive models of sediment flux at the landscape scale.

Currently, our ability to predict the flux of fine sediment at the watershed scale is limited by the precision of geomorphic change detection over vast areas, our understanding of the (dis-)connectivity of sediment pathways during transport through the terrestrial environment and channel–floodplain complex (Fryirs et al. 2007), and a general inability to recognize and account for historical contingencies related to the erosional and depositional history of a landscape (Phillips 2006). Considering these limitations, Smith, Belmont, and Wilcock (2011) list four elements needed to advance sediment prediction at the landscape scale: (1) specificity regarding location, mechanism, and rates of erosion; (2) accurate accounting of sediment storage; (3) appropriate methods for upscaling local observations; and (4) efficient means for incorporating multiple lines of evidence to constrain sediment budgets.

At the "local" (plot) scale, erosion rates are most commonly estimated using the empirical universal soil loss equation (USLE) or some derivative thereof (i.e., RUSLE, MUSLE, etc.; Wischmeier and Smith 1978; Renard et al. 1997; Soil and Water Conservation Society 2003). In the absence of a process-based predictive model for sediment routing, empirical parameters such as the sediment delivery ratio (SDR) and the relation of upstream contributing drainage area (A) to area-specific sediment yield (SSY) are used to extrapolate local erosion estimates to predict sediment production at the watershed scale (Walling and Webb 1996). Such approaches are difficult to constrain in reality, however (Trimble and Crosson 2000). SSY is typically assumed to be inversely proportional to A due to the prevalence of sediment sinks at larger spatial scales. Although this assumption holds for many watersheds across the world, many factors influence the nature of this relationship. Estimates of SSY for watersheds of the same drainage area can vary up to four orders of magnitude due to differences in physical erosion processes, topography, weather, climate, and land use (de Vente et al. 2007). Further, the A–SSY relationship can change over time and even become positively correlated as sediment sources shift from upland erosion to near-channel erosion (Birkinshaw and Bathurst 2006). Even in cases where SDR or the A–SSY relationship can be calibrated from direct measurements of sediment in transit, models are unable to account for shifts in sediment sources and account for all methods of sediment generation (i.e., deep gully erosion, wind erosion, debris flow, and landslide processes; Boomer, Weller, and Jordan 2008).

Pelletier (2012) recently developed a spatially distributed model to predict long-term fine sediment discharge in large watersheds from slope, soil texture, rainfall, and leaf area index, using only two free calibration parameters. Although this approach is useful over large spatial and long temporal scales, a more detailed and precise understanding of landscape sediment dynamics is needed in 10^1–10^4 km^2 watersheds, especially to inform management and stream restoration and rehabilitation decisions.

Recently, forty-three reaches of the Root River watershed in southeastern Minnesota were listed as impaired under section 303d of the U.S. Clean Water Act (Minnesota Pollution Control Agency [MPCA] 2010). Of the forty-three reaches, 73 percent are impaired for turbidity and mercury. Excessive sediment loads combined with regulatory requirements to reduce sediment loading sparks several key questions: Where is the sediment coming from? What proportions of the sediment are from upland versus near-channel erosion? How much of the excessive sediment loading is caused by modern land use and water management versus the legacy of past land use?

The goals of this study were to (1) understand the erosional and depositional history of the Root River watershed and the implications for modern erosional processes and (2) identify potential sources and sinks distributed throughout the watershed and constrain contributions from source areas. In the following sections, we describe relevant characteristics of the study area and the range of methods employed. We then describe the results of geomorphic and hydrologic analysis, respectively, and discuss sediment fingerprinting results for source areas and suspended sediment.

Study Area

The 4,300 km^2 Root River watershed in southeastern Minnesota is located partially within the unglaciated Driftless Area of the upper midwestern United States (Syverson and Colgan 2004). This region is underlain by Paleozoic limestone and dolostone, with occasional outcrops of St. Peter sandstone (Dogwiler 2010). Topography is moderately dissected, characterized by deep valleys and rolling uplands. Alluvial valley bottoms are flat and typically farmed for corn and soybeans. Many steep upland areas (> 10° slopes) are forested, but row-crop agriculture and grass-covered pasture typically occur on slopes less than 10°, which make up roughly three quarters of the watershed area. The western third of the watershed was glaciated during the Last Glacial Maximum (LGM) and is characterized by exceptionally flat topography, underlain by fine-grained till, and intensively used for row-crop agriculture. Current land uses for the entire watershed as well as subwatersheds are reported in Table 1.

Prior to European American settlement circa 1830, nearly the entire watershed was dominated by upland prairie and oak savanna plant communities (University of Wisconsin–Madison 1990; Dogwiler 2010). Native Americans hunted buffalo in the area and used fire to clear dense prairie grasses and induce regrowth to entice buffalo and other game into the area (Marks 1942). Discovery of lead ore in the region attracted many early settlers (Schockel 1917), who would switch between mining and agriculture depending on the price of lead. As mining interests moved west, population and agricultural intensity steadily increased (Lueth 1984; Dogwiler 2010).

The evolution of farming practices is relevant to understanding modern sediment dynamics insofar as the legacy of past farming practices might still be influencing the river today via legacy deposits. Farming practices of European American settlers often gave little regard to topography when plowing and developing fields for crops. Furrows that ran “up and down” slope worked well in Northern Europe where precipitation was on the order of 25 cm per year (Dogwiler 2010). High-intensity rainfall events often caused notable gully erosion on many fields and often decimated crops (Surber 1924). In the early 1900s, farmers began to plow cross-slope, plowing directly to the water’s edge of rivers and streams to maximize production. With tractors becoming common in the mid-1900s, farming down to the river’s edge

Table 1. Percentage of land use for Root River and tributaries

		Percentage of watershed by land use					
Watershed	Area (km^2)	Developed	Forest	Grassland	Pasture	Crops	Other
Bridge Creek	8	5.5	0.3	9.8	22.2	62.3	0.0
Crystal Creek	41	5.1	8.5	13.0	22.6	50.5	0.2
Money Creek	153	4.6	44.6	10.0	29.9	10.4	0.4
South Branch Root River	736	5.6	15.3	10.9	10.9	47.2	10.2
South Fork Root River	702	4.2	24.8	11.8	26.3	32.7	0.2
North Branch Root River	1,464	6.6	10.6	11.1	15.1	56.0	0.6
Main Stem Root River	4,100	5.4	20.8	10.5	20.2	42.4	0.7
Root River Watershed	4,299	5.3	22.0	10.3	20.4	41.1	1.0

was not practical and moved away from the river and steeper hillslopes onto flat uplands and terraces (Dogwiler 2010).

Surber conducted the first biological reconnaissance of the Root River in 1924. He primarily assessed suitability of the river for aquatic biota but noted apparent high erosion rates in the Root River watershed, consistent with land use degradation noted throughout the upper Midwest about this same time period (Trimble and Crosson 2000). Estimated erosion rates, from the onset of European settlement to the 1930s, indicate that nearly 4 cm of soil, on average, was eroded from hillslopes in the Driftless Area, the majority of which was subsequently deposited in local floodplains (Knox 1977, 2001, 2006; Trimble 1999).

Soil conservation practices were first implemented in the Root River watershed in the late 1930s. A wide range of conservation practices are in use today, including conservation tillage, grass buffer strips, water and sediment detention basins, and overwinter crop cover. The extent to which these conservation practices have actually reduced erosion rates has not been constrained at the watershed scale, however. Prior work done by Beach (1994) estimated SDR and sediment storage using USLE in three small (17–144 km^2) watersheds in southeastern Minnesota, one of which is a tributary to the Root River (Beaver Creek, tributary to the South Fork). Results from his work suggest that upland erosion decreased during the period 1851 to 1988. During that time frame, much of the eroded sediment was stored in the floodplains. Beach (1994) concluded that further study is necessary to identify the fractions of sediment sourced from upland versus near-channel erosion.

Trimble (1999), working in Coon Creek, Wisconsin, immediately across the Mississippi River from our study area, also demonstrated a postsettlement (late 1800s, early 1900s) pulse of excessive erosion on uplands and agricultural fields, followed by gradual slowing of erosion rates due to changing land use practices. Most sediment liberated from hillslopes and fields remained within the watershed, stored in the channel–floodplain complex. Given similarities in geologic and geomorphic context, climate, vegetation and land use history, and base level control, it is reasonable to expect a similar story to have played out at the larger scale of the Root River watershed. Thus, the history documented for Coon Creek and Beaver Creek serves as a conceptual hypothesis for our study in the Root River watershed and provides a basis for our study design and sampling strategy.

Methods

This study employed a variety of techniques to understand the recent hydrologic and geomorphic evolution of the landscape and identify potential sediment sources and sinks. The following sections describe methods used to investigate the hydrologic and geomorphic history of the watershed. The methods continue to explain how sediment fingerprinting samples were collected, prepared, and measured for concentrations of beryllium = 10 (^{10}Be), excess lead = 210 (^{210}Pb), and cesium = 137 (^{137}Cs).

Longitudinal Profile Analysis

The slope of a river channel typically decreases as a power function of drainage area as flow increases in the down valley direction (Mackin 1948). In certain cases, however, slope locally increases or decreases at an anomalous rate in the downstream direction. These anomalous zones where channel slope increases or rapidly decreases are known as *knickzones* or *knickpoints* (depending on their spatial extent), which occur in response to an external control such as bedrock, change in base level, or a change in sediment flux, caliber, or both. These locations are useful to identify insofar as they represent discontinuities in the sediment routing system. Longitudinal profiles for all major tributaries were extracted from a 30-m digital elevation model (DEM; data from http://nationalmap.gov/viewer.html) using the Stream Profiler Tool available from http://www.geomorphtools.org. Elevation, slope, and contributing area were compared for each of the major tributaries to identify anomalously steep reaches (knickzones) and anomalously low gradient reaches, which might be sediment sinks. Knickzones identified from slope-area analysis were mapped in ArcMap (ESRI 2011) and then visually compared to transitions in geologic substrate, the number of terraces, and the heights of terraces in those zones.

Automated Mapping of Floodplains and Terraces

Understanding the regional pattern of terrace development and preservation can aid in development of sediment budgets (Finnegan and Dietrich 2011; Gran et al. 2011; Pazzaglia 2013), thus being useful in land and water management decisions. Terraces adjacent to the channel are potential net sources of sediment, especially if there is a large elevation difference between the surface being eroded and the floodplain and point bar being constructed on the opposite bank (Lauer and Parker 2008).

Terraces in the Root River were delineated using the TerEx tool, which semiautonomously extracts and maps terraces from a light detection and ranging (LiDAR)-derived DEM and measures their absolute elevation and height relative to the nearby stream channel (Stout and Belmont 2013). In the Root River, we used the TerEx tool to extract terraces based on three user-specified attributes: (1) local relief of the terrace could not exceed 0.5 m within a 500-m^2 area; (2) the surface must be within 100 m of the channel centerline; and (3) the area of the surface, once identified, could not be less than 500 m^2. All surfaces selected by the tool were ground-truthed to ensure that these features were alluvial deposits and not upland agricultural fields. Based on field observations, we defined floodplains as surfaces that were less than 2.0 m above the channel. Alluvial surfaces higher than that threshold were considered terraces, the majority of which are fill terraces, although several strath terraces have been identified within the bedrock reaches of the river network.

Hydrologic Analysis and Suspended Sediment Flux

The Fillmore County Soil and Water Conservation District (SWCD), in conjunction with MPCA and the U.S. Geological Survey (USGS), has installed numerous water and suspended sediment gaging stations in key locations (Figure 1) along the Root River and major tributaries. Hydrologic analysis was performed on the available data set from USGS gage number 05385000 near Houston, Minnesota. Daily flow data were extracted from 1909 to 2010 and peak flow data from 1910 to 2011. Flow duration curves were produced for each decade. Flood frequency–magnitude relationships were developed using the Log Pearson Type III method

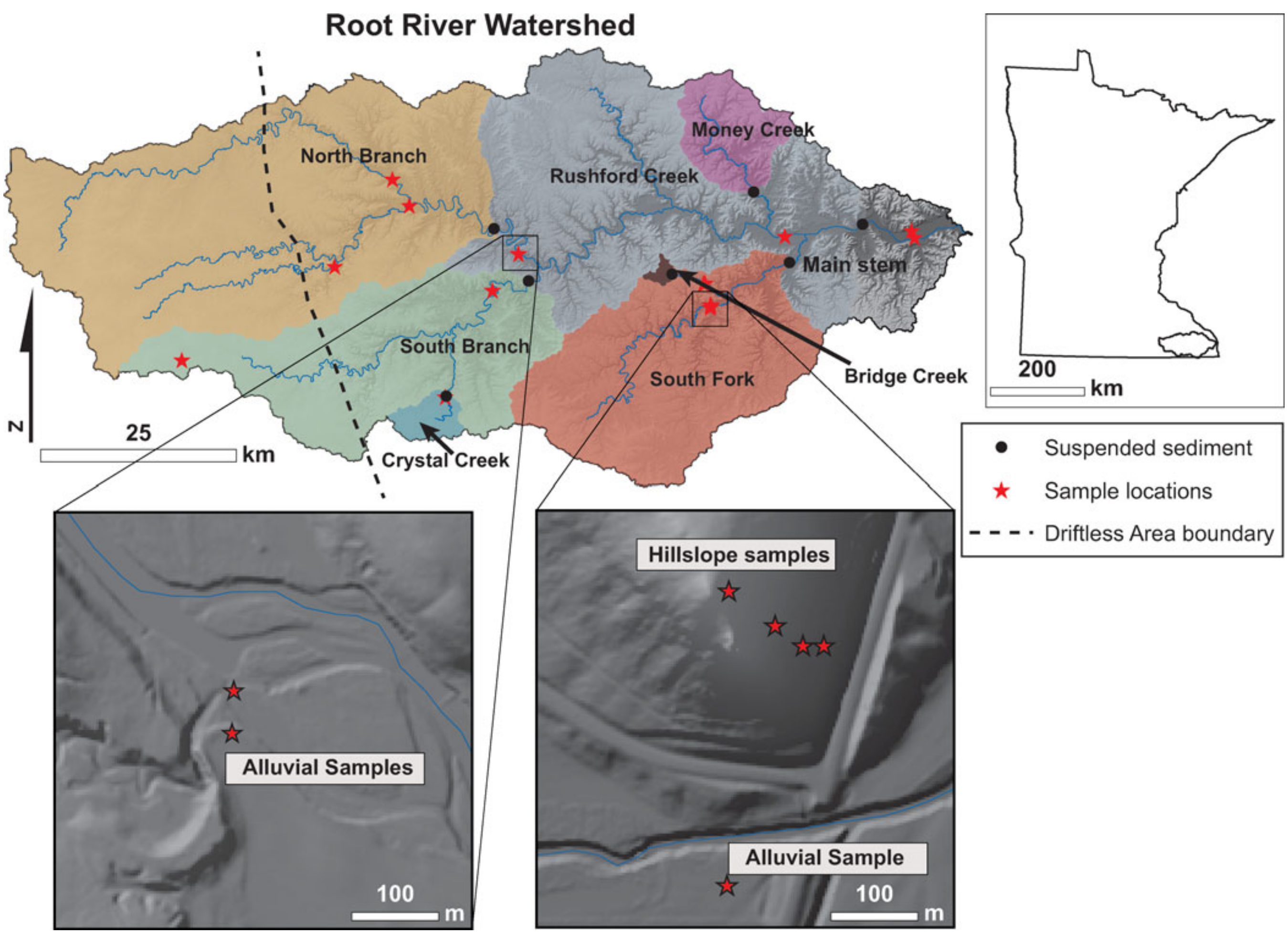

Figure 1. Location of the Root River watershed in Minnesota. Fingerprinting source samples are indicated by stars, suspended sediment sample locations and gaging stations are indicated by dots. (Color figure available online.)

to calculate the 2-, 10-, 25-, 50-, 100-, and 200-year return interval events for the watershed.

Fillmore County SWCD used FLUX[32] version 3.03 to estimate annual loads at five suspended sediment monitoring locations (Figure 1), including North Branch, South Branch, South Fork, Money Creek, and the main stem of the Root River. Approximately forty samples were collected on the rising and falling limb of storm hydrographs as well as base flow, and annual loads were computed at each site from May to October for 2008, 2009, and 2010. Data from the North Branch location were not available for 2008; however, loads were estimated for 2008 using averages from 2009 and 2010 data. Estimates were also made for a second ungaged watershed, Rushford Creek (350 km^2), using data collected from Money Creek, which has similar lithology, land use, and longitudinal profile shape.

Sediment Fingerprinting

Sediment fingerprinting provides key information regarding the relative contributions of different sources as well as transport pathways through the landscape. Such information could be used to validate sediment yield models, helping to unlock the "black box" of sediment delivery (Walling 1983; Burt and Allison 2010). Sediment fingerprinting using long- and short-lived radionuclide tracers can be employed to (1) determine the relative proportion of sediment derived from upland versus near-channel erosion, (2) understand whether and how the rates of sediment supply from those sources has changed over time, and (3) identify what pathways and sinks exist within the watershed (Gellis and Walling 2011). When analyzing radiogenic tracers, the combined use of multiple tracers with disparate half-lives is useful because the results of analysis with any individual tracer tend to develop a bias depending on storage time within the landscape and channel–floodplain network. Specifically, long-lived tracers continue to accumulate, whereas short-lived tracers decay during transport, storage, and resuspension in the channel–floodplain network (Lauer and Willenbring 2010; Viparelli et al. 2013).

Primary sediment sources in the Root River watershed include uplands (both agricultural and nonagricultural land), ravines, and stream banks. We used three radionuclides, ^{10}Be, ^{210}Pb, and ^{137}Cs, with half-lives of 1.39×10^6 years, 22.3 years, and 30.2 years, respectively, to apportion sediment sources at the gaging stations for five subwatersheds of the Root River. This particular suite of geochemical tracers associated with suspended sediment has been used to distinguish between upland versus near-channel sources (Belmont et al. 2011). The combination of long- and short-lived radiogenic tracers brackets the actual contributions from upland versus near-channel sources, providing maximum and minimum estimates of source contributions, respectively.

Long-Lived Tracer Beryllium-10. Meteoric beryllium-10 has a half-life of 1.39 million years (Chmeleff et al. 2010) and is produced in the atmosphere when cosmic rays collide with the nuclei of atmospheric gases. Meteoric ^{10}Be is delivered to the Earth's surface by dry deposition or precipitation. The flux of ^{10}Be to the Earth's surface varies over time with the intensity and orientation of the geomagnetic field (Pigati and Lifton 2004) and is dependent on atmospheric mixing, precipitation, and wind patterns (Field et al. 2006; Heikkilä 2007; Masarik and Beer 2009). The two primary models used to predict delivery of meteoric ^{10}Be (Field et al. [2006] using the Goddard Institute for Space Studies Model E and Heikkilä [2007] using the European Centre for Medium-Range Forecasts-Hamburg Model 5) are in close agreement in our study area, indicating relatively high delivery rates (10^6 at/cm^2/yr).

Once ^{10}Be has been scavenged from the atmosphere and delivered to the Earth's surface, it binds tightly to soil particles within the top 1 to 2 m below the surface. The depth profile of ^{10}Be typically exhibits a maximum concentration at the surface and decreases with depth. Given the deep adsorption path of ^{10}Be, the depth profile is not significantly affected by the plow layer in agricultural soils. Factors such as the acidity or alkalinity of the soil control the adsorption competition that ^{10}Be experiences with other metals. In the alkaline soils of the Root River watershed, adsorption competition is small, so ^{10}Be binds tightly to soil particles. Grain size and organic matter content of the soil can also affect meteoric ^{10}Be concentrations. Other external factors that can affect the measured concentration of ^{10}Be in the soil profile include the addition of dust particles, retentivity of ^{10}Be by soil and water, and the heterogeneous nature of soil properties, hydrology, and historic erosion rates throughout the watershed. All of these factors result in a spatially variable concentration of ^{10}Be. Therefore, we based our sampling strategy on our understanding of how delivery, production, and erosional processes redistribute ^{10}Be throughout the landscape and channel–floodplain network. For a comprehensive review of meteoric ^{10}Be systematics, see Willenbring and von Blanckenburg (2010).

Short-Lived Tracers Lead-210 and Cesium-137. Lead-210 is produced both in the atmosphere (referred to as meteoric or unsupported) and inside the mineral grains of the soil (in situ or supported; Noller 2000). Both are created through the decay chain of ^{238}U and have a half-life of 22.3 years. Once produced in the atmosphere, meteoric ^{210}Pb is deposited through rainfall and adsorbs to fine silts and clays, typically within the top 5 cm of the soil surface. In agricultural fields, ^{210}Pb is mixed throughout the plow depth (approximately 25 cm). Sediment derived from sheet wash and rill erosion typically exhibits relatively high concentrations of ^{210}Pb compared to deeper erosion such as gullies or ravines.

Cesium-137 has a half-life of 30.2 years and like ^{10}Be and ^{210}Pb has a strong affinity for soil particles. Cesium-137 was delivered through atmospheric deposition as a result of above-ground nuclear weapons testing during the period from 1950 to 1963. The initial distribution is assumed to be spatially uniform over small watersheds, although variations are seen among and within large watersheds (Owens, Walling, and He 1996). Cesium-137 has been used to trace suspended sediment through watersheds and investigate floodplain deposition rates (Collins, Walling, and Leeks 1997; Walling and He 1998; Gellis and Walling 2011). Parsons and Foster (2011), however, noted that ^{137}Cs might be (1) lost via plant uptake and harvesting; (2) released from sediment due to weathering of minerals or addition of NH_4 or K; and (3) leached via dissolved organic compounds. For both ^{210}Pb and ^{137}Cs, the actual concentrations found throughout the landscape are influenced by the erosional and chemical heterogeneities of the landscape, dilution that occurs when tracer-rich sediment is mixed with tracer-deficient sediment, as well as the time spent in storage reservoirs (e.g., floodplains) during routing through the watershed.

Expected Concentration of Tracers in Source Areas. Indicators of the landscape erosional history are archived in the floodplains and fill terraces surrounding the channel network. This erosional history influences sediment loads contributed from different parts of the watershed as well as the concentrations of geochemical tracers in upland (hillslopes and agricultural fields) and alluvial (channel, floodplains, and terraces) sediments. For example, assuming that the history of the Root River closely follows that documented for Coon Creek, we hypothesize that hillslopes and agricultural fields throughout the Root River watershed should be relatively depleted of meteoric ^{10}Be (due to historic stripping of ^{10}Be-rich soil), yet exhibit relatively high concentrations of ^{210}Pb and ^{137}Cs, due to accumulation in recent decades.

Further, assuming that the Root River is currently reworking vast legacy sediment deposits, we expect to find many large, near-channel terraces with a significant difference in elevation between the depositing and eroding surfaces. We also expect to find indicators of rapid post-settlement erosion archived in floodplain stratigraphy or alluvium stored in small dams throughout the watershed. In this scenario, floodplains should exhibit an inverted ^{10}Be profile (higher concentrations at depth), indicating initial erosion of ^{10}Be-rich soil and storage in the floodplains, followed by erosion and storage of ^{10}Be-poor soil. Alternatively, a uniform tracer concentration with depth would indicate relatively steady and uniform erosion and subsequent deposition in the floodplain. Due to the long duration of storage, we expect floodplain and terrace sediment to contain little to no ^{210}Pb and ^{137}Cs other than a thin veneer (5–10 cm) at the surface, due to atmospheric deposition over the past few decades. We contend that this veneer contributes a negligible amount of tracer relative to the 2 to 6 m of sediment contributed when any given bank is eroded, the vast majority of which contains no ^{210}Pb or ^{137}Cs.

Geochemical Tracer Sampling: Terrestrial/Alluvial Sample Collection and Preparation

Potential sample locations were selected using a combination of information from aerial photos, 3-m-resolution LiDAR DEM analyses, maps of fluvial terraces, and input from state and local agency staff. Terrestrial samples, including hillslope and agricultural field samples, were selected in locations that were expected to represent the range of historic variability in erosion rates and resulting tracer concentrations. Further agricultural field samples were collected by Minnesota Department of Agriculture (MDA) staff during storm events via edge-of-field samplers. Six hillslope soil samples were collected from soil pits dug along catenas.

Fourteen alluvial samples were collected as cores from floodplains and terraces to compare the geochemical signatures of what had been historically transported by the river with what is currently transported. Each surface was cored to the maximum auger length (2.2 m) or until gravels or the water table was reached. Each core was divided based on changes in texture, color, or both. If no changes were apparent in the sediment core, four composite samples were collected along the length of the core for geochemical analysis. The stars in

Figure 1 indicate source sample locations where multiple samples were collected at each location marked by a star.

Samples were dried and a mortar and pestle was used to break up pedogenic amalgamations. Samples were sieved to $< 125\ \mu$m and further split into three subsamples. One subsample was sent to the Purdue Rare Isotope Measurement Laboratory (PRIME Lab) for ^{10}Be extraction, isolation, and measurement via accelerator mass spectrometry (AMS). Another subsample was sent to the St. Croix Watershed Research Station for ^{210}Pb and ^{137}Cs analysis by alpha and gamma particle emission. The third subsample was analyzed for grain size distribution using a Sequoia Scientific LISST-Portable laser diffractometer, assuming an irregular grain shape (Sequoia 2011). Output data from the grain size analysis included the median grain size (D_{50}), skew of distribution, standard deviation, and surface area.

Given that smaller grain sizes have more surface area per unit mass, concentrations of tracers in coarser material might need to be normalized. Corrections to ^{210}Pb and ^{137}Cs results were accomplished using the ratio of the measured surface areas of the suspended sediment and source area materials (Collins et al. 1997; Walling 2005). Corrections to ^{10}Be concentrations were made following the technique of Willenbring and von Blanckenburg (2010; see their Equation 3), where N_c is the corrected concentration of the tracer, N_t is the initial concentration of the tracer, $SA_{\text{measured, reference}}$ are the surface areas of the measured and reference sediment and γ is the power law exponent that describes the relationship between grain size and tracer concentration, typically –0.5 (±0.1). Using Equation 1, each floodplain and hillslope sample was corrected using the suspended sediment samples as the reference surface area.

$$N_c = N_\tau \left(SA_{measured}/SA_{reference}\right)^{\gamma} \qquad (1)$$

We did not use a single reference surface area for the entire watershed; rather, hillslope and floodplain samples were corrected by suspended sediment samples from the corresponding subwatershed. For example, the floodplain and hillslope samples from Bridge Creek were corrected by the grain size of suspended sediments collected at the Bridge Creek sample site. Grain size corrections, for all source samples, were made for ^{210}Pb/^{137}Cs and ^{10}Be.

Geochemical Tracer Sampling: Suspended Sediment Sample Collection and Preparation

Sediment fingerprinting samples were collected by the Fillmore County SWCD during snowmelt and rainfall runoff events, with a goal of collecting two samples on the rising limb of the hydrograph and two on the falling limb for each sampling event. A minimum of seventy-five liters of water was collected for each sample to ensure enough sediment was available for analysis. After collection, sediment was allowed to settle over the following three to four days, after which sediment-free water was siphoned off. The settling process was repeated until the sample volume was less than one liter, at which time the sample was shipped to the respective labs for ^{10}Be, ^{210}Pb/^{137}Cs, and grain size analyses.

Results and Discussion

Hydrologic and Geomorphic Analysis

Longitudinal Profiles and Distribution of Terraces Throughout Watershed. Longitudinal profiles extracted from the 30-m DEM were analyzed for the presence of knickpoints. Profiles shown in Figure 2 indicate the presence of several diffuse knickpoints, from here on referred to as knickzones. The primary knickzones on the North Branch, Root River, Bear Creek, and South Branch all coincide with the boundary between glaciated and unglaciated (driftless) terrain.

Mapped terraces and floodplains throughout the watershed provided a general context for likely sediment sources and potential areas of storage (Figure 2B). When compared with the longitudinal profiles (Figure 2A), the map of floodplains and terraces indicates that the presence of near-channel terraces increases downstream from the knickzones (upright triangles), suggesting an increased potential for near-channel sediment sources in this portion of the channel network. Two locations in the center of the map (downward triangles) were areas of anomalous decreases in slope. These areas are prone to sediment storage due to reduced stream power.

The map of terraces provided insight regarding the height of banks along each section of the river and was used in selection of sampling locations. Figure 3 illustrates the cumulative distribution of bank heights adjacent to each tributary of the Root River. An example of how to read the plot is given in Figure 3C. Based on the terrace map developed for the Root River, we can see that approximately 80 percent of the South

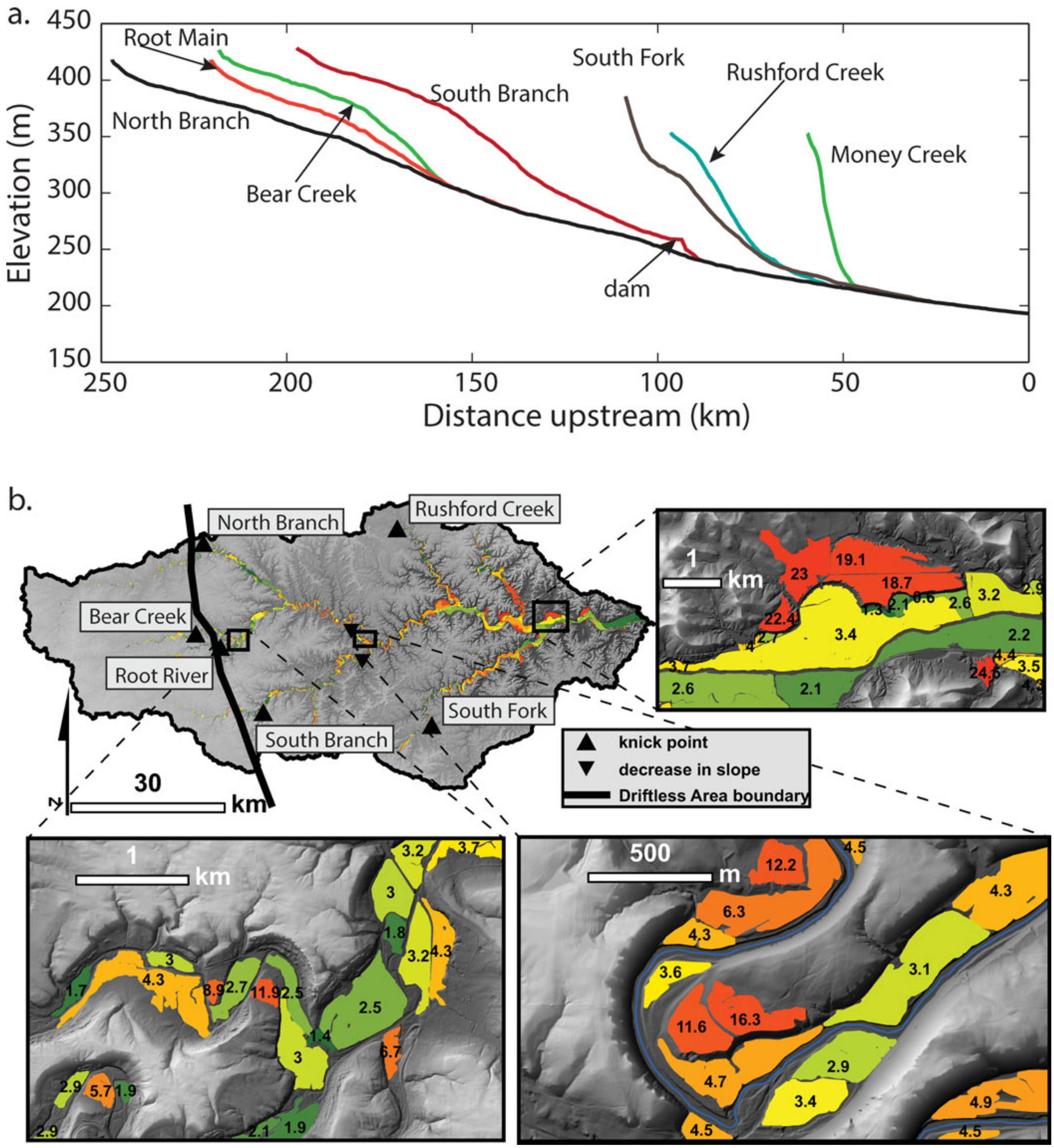

Figure 2. (A) Longitudinal profiles for all major branches and tributaries. (B) Knickpoint locations throughout the watershed. Upward triangles indicate the start of knickpoints. Downward triangles are areas of anomalous decreases in slope. Inset images are examples of mapped terraces with heights measured relative to the local channel. (Color figure available online.)

Fork of the Root River is lined with terraces greater than 2 m tall. From Figure 3, plot A, 70 percent of the main stem of the Root River is lined by terraces greater than 4 m tall. Reaches of the river network characterized by significantly taller-than-average stream banks likely receive larger net sediment contributions from channel migration or widening (Lauer and Parker 2008; Smith et al. 2011).

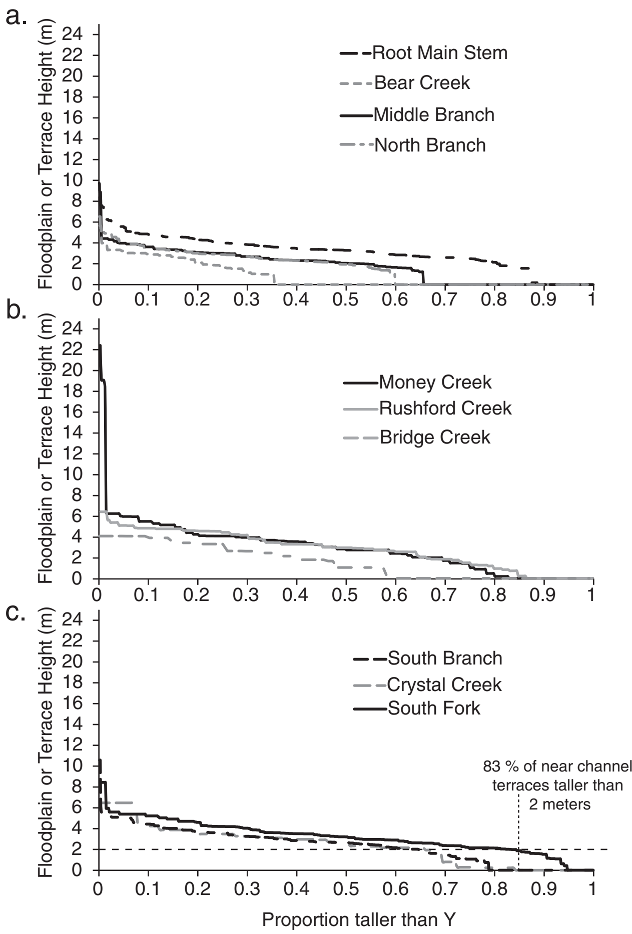

Figure 3. Cumulative distributions for floodplains and terraces for all major tributaries. Based on field observations, we define terraces as near-channel alluvial features that are higher than 2 m above the local channel. See Figure 1 for tributary locations.

Hydrology and Suspended Sediment Flux Data. Decadal flow duration curves (1910–2011) indicate significant increases in both high (10 percent exceedance) and low (90 percent exceedance) flows since 1930 (Figure 4A). High flows have increased in magnitude by 60 percent and low flows increased by 80 percent. After the 1980s, flow durations stabilized somewhat, although the top 5 percent exceedance flows have increased by 20 percent over the last decade.

Several factors might have influenced the shift in flow duration curves. In the early 1970s, agriculture began to shift from small grains and grass pasture to corn and soybeans. Around this same time, both the density and efficiency of subsurface drain tiles increased, although the rates and densities of installation are not well known. Although long-term records of precipitation data for the Root River watershed are sparse and discontinuous, increases are observed (i.e., not statistically significant) in mean annual precipitation, as well the duration and intensity of storm events. Similar increases in flow and precipitation have been observed elsewhere throughout Minnesota and have been attributed to a combination of increased precipitation, changes in crop type, and artificial subsurface drainage. An increase in the midrange and high flows can induce channel widening, bank erosion, and channel scour, all of which can contribute to increased sediment yield from the watershed (Schottler et al. 2013).

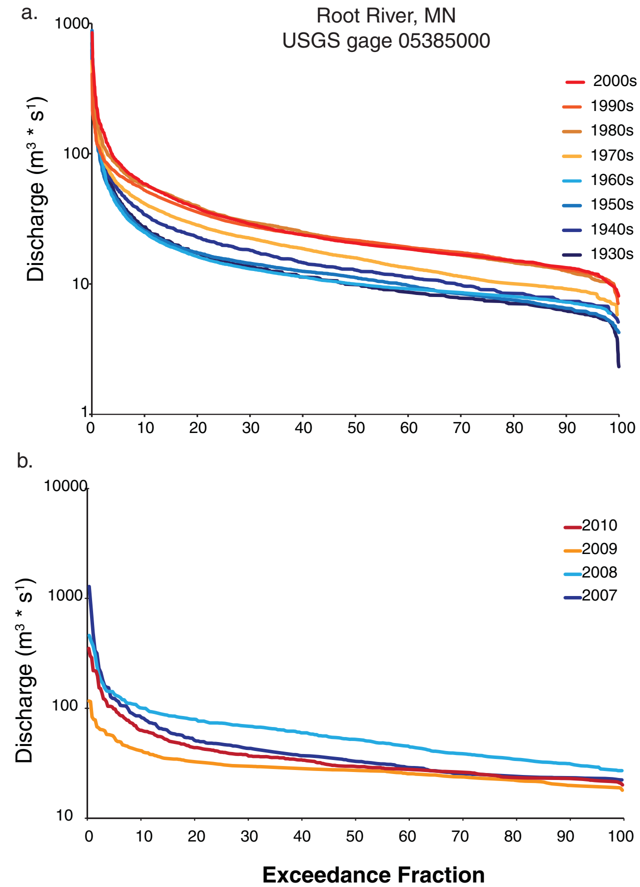

Figure 4. (A) Decadal flow duration curves for entire flow record. (B) Annual flow duration curves for years 2007 to 2010. (Color figure available online.)

A year-to-year comparison of sediment flux data from subwatersheds illustrates the important role of hydrology in watershed scale sediment dynamics. Table 2 reports annual suspended sediment loads in 10^3 Mg/year and annual suspended sediment yield in Mg/year/km^2. For years 2008 and 2009, gaged tributaries contributed a mass of sediment that is roughly equal to or greater than the mass passing the gage near the mouth of the river. Considering the fact that additional sediment is contributed from the ungaged

Table 2. Sediment flux (10^3 Mg/year) and sediment yield (Mg/year/km^2) for years 2008 to 2010

		Sediment flux (10^3 Mg/year)			Sediment yield (Mg/year/km^2)		
Sample location	Area (km^2)	2008	2009	2010	2008	2009	2010
North Branch	1,465	44[b]	47	42	30[b]	32	29
South Branch	737	73	8	47	99	10	64
South Fork	711	121	15	51	170	21	71
Money Creek	153	10	1	9	64	5	59
Rushford Creek[a]	348	22[c]	2[c]	21[c]	64[c]	5[c]	59[c]
Main stem	4,121	186	64	366	45	15	89
		2008	2009	2010			
Minimum net storage on main stem[d]		18	6	−217			
Total estimated storage on main stem[e]		84	7	−197			

[a]Ungaged watershed.
[b]Sediment load for 2008 was estimated as an average of 2009 and 2010 sediment yields.
[c]Values are estimated using sediment yields from Money Creek.
[d]Assumes ungaged watersheds contribute zero sediment.
[e]Includes estimates from ungaged watersheds.

reaches, these data strongly suggest that 2008 and 2009 were years of net storage along the main stem of the Root River. Minimum net storage in the main stem was computed assuming zero contributions from ungaged portions of the watershed (an unlikely scenario, but useful minimum constraint), whereas total estimated net storage assumes loading from ungaged portions based on estimated yearly loads from the North Branch (only for 2008) and Rushford Creek (all years). In contrast to years 2008 and 2009, tributaries in 2010 contributed roughly 149 × 10^3 Mg, yet nearly 366 × 10^3 Mg of sediment passed the gage near the river mouth, indicating a net evacuation of stored fine sediment within the lower reaches of the river.

It is likely that errors and uncertainties associated with computing annual sediment loads contribute to the disparities observed, but the magnitude of the differences in loads is well above the expected uncertainty of the method (~20 percent). Nevertheless, the rudimentary sediment budget presented here should only be used as support for the possibility of a storage and release phenomenon. The notion that the main stem Root River acts as both as a source and a sink at different times is consistent with our geomorphic understanding of this dynamic alluvial system.

Sediment Fingerprinting

Upland Tracer Concentrations: Agricultural Fields and Hillslope Tracer Profiles. Figure 5 illustrates the spatial and vertical distributions of ^{10}Be concentrations found in hillslope soil profiles. We collected profiles from transects along two hillslopes in the Bridge Creek and South Fork Root River watersheds. A typical ^{10}Be profile in an undisturbed surface is expected to have a maximum concentration at the surface and decreasing concentration with depth, as observed in samples H3, H4, and H5. On average, the surface layer of undisturbed hillslope soils exhibits an average ^{10}Be concentration of 8.2 × 10^8 at/g. Depth profiles observed in the Bridge Creek watershed (H1 and H2) exhibit relatively low concentrations (6.6 × 10^8 at/g), indicative of rapid historic erosion. Field observations noted evidence of substantial erosion (stripping of topsoil layer, little to no plant litter at the surface, and exposed plant roots) at these sites. Sample locations H2 and H5 were noted as having truncated A horizons and location H6 was noted as an area of colluvial deposition at the base of the slope, apparent in the elevation profile of the transect (Figure 5B). Thus, hillslopes that have experienced some historic stripping of topsoil exhibit slightly lower concentrations and at least some of that stripped soil appears to be stored locally at the toe of the hillslope. Nevertheless, hillslope soil surfaces maintain a fingerprint concentration in the range of 9.1 to 7.1 × 10^8 at/g.

Hillslopes exhibit a measurable concentration of excess ^{210}Pb at the surface, which declines to a concentration of zero within a few centimeters. Sample locations H2 and H5, which had truncated A horizons, had

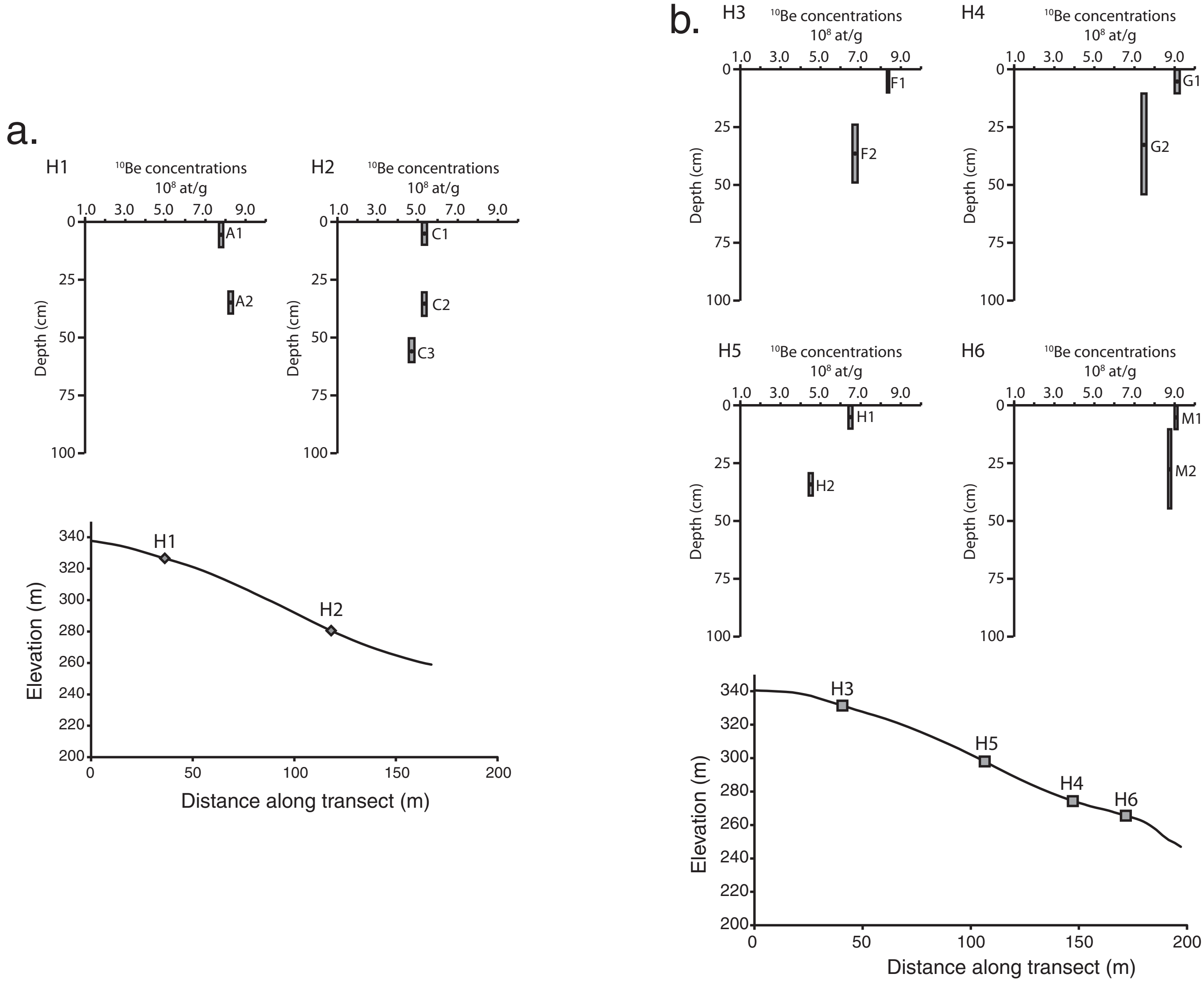

Figure 5. Hillslope sample locations and ^{10}Be concentration profiles. Sample names are H1, H2, and so on. The H indicates that the sample was taken from a hillslope. All concentrations are normalized for grain size. (A) Sample pattern and results collected on Bridge Creek (see Figure 1). (B) Sample pattern and results collected on the South Fork (see Figure 1).

the lowest concentrations (1.58 and 2.66 pCi/g, respectively), whereas the other hillslope sample locations consistently ranged from 2.66 to 3.9 pCi/g. Cesium-137 exhibited a similar trend. Due to space constraints, we only report the ^{210}Pb results, as both ^{210}Pb and ^{137}Cs provide redundant information.

Samples used to determine tracer concentrations of sediment from agricultural fields included a combination of sheet wash collected by automatic edge-of-field samplers and shallow core samples (< 0.25 m) collected along a uniform grid by MDA staff. After correcting for grain size, agricultural fields have an average ^{10}Be concentration of 5.0×10^8 at/g with a standard deviation of 1.6×10^8 at/g, indicating that either surface erosion has historically been higher on agricultural fields than hillslopes or that agricultural soils systematically retain less ^{10}Be than do hillslope soils. A single sample (F14), taken from an agricultural field in the glaciated region, serves as a representative fingerprint for agricultural fields within the glaciated region. The fingerprint for agricultural fields within the unglaciated region was compiled from multiple edge-of-field samplers during storm events.

Floodplain Tracer Profiles. Floodplains are useful, if incomplete, archives of past sediment dynamics. In general, active floodplains throughout the Root River watershed are devoid of meteoric ^{210}Pb and ^{137}Cs and exhibit inverted ^{10}Be profiles (Figure 6, site F8). The absence of meteoric ^{210}Pb and ^{137}Cs indicates that these floodplains were built more than seventy-five years ago and the inverted ^{10}Be profiles suggest that they are the result of a pervasive topsoil stripping event. Depth profiles of tracer concentrations in the floodplains are somewhat variable, however, reflecting the heterogeneous nature of land use effects throughout the watershed.

It is possible that the inverted ^{10}Be profiles record sediment eroded prior to pervasive plowing of the uplands. Initial plowing would have mixed the ^{10}Be-rich sediment at the surface with lower ^{10}Be concentrations that occurred lower in the soil profile. This scenario is plausible but unlikely to be a dominant cause for the observed inverted floodplain profiles. To account for the observed difference in ^{10}Be concentrations, the plow depth would need to have thoroughly mixed the top 0.75 m. Lindstrom, Nelson, and Schumacher (1992) stated that in Minnesota plowing practices over the last century have varied but have typically been around 0.25 m. Thus, the lower ^{10}Be concentration measured on agricultural fields is a combination of catastrophic stripping of the topsoil, combined with mixing from plowing practices.

In the Bridge Creek watershed, geomorphic observations and hillslope ^{10}Be profiles indicated relatively rapid historic erosion. The ^{10}Be depth profile of a floodplain core (F8) from Bridge Creek is consistent with these observations. Specifically, the ^{10}Be concentration is inverted, indicating that ^{10}Be-rich soil was stripped from the hillslopes and stored in the floodplain at some point in the past. Bridge Creek is a small (19 km^2) tributary to the South Fork Root River. At the head of the drainage, an automated edge-of-field sampler established by MDA captures sediment being sourced directly from contributing agricultural fields. Edge-of-field sample locations indicate that the concentration of ^{10}Be associated with sediment derived from agricultural fields is in the range of 5.7×10^8 to 6.3×10^8 at/g, similar to concentrations observed in the surface layer of the floodplain (Figure 6, site F8).

Each floodplain and terrace profile recorded information about upstream sediment sources and erosion rates over time. Useful information can be derived from the broader patterns in the tracer concentrations and profiles. Categorizing the floodplain and terrace surfaces as young or old facilitates interpretation. In the context of the Root River floodplains and terraces we define young surfaces as floodplains that have been built within the last 100 years. Older floodplains are detached from the channel or contain other evidence supporting the assumption that the surface is likely older than 100 years (i.e., old-growth vegetation, soil pedogenesis). Young floodplain surfaces (F1, F2, F4, F5, F6, F9, and F12) exhibit relatively uniform ^{10}Be depth profiles with concentrations between 3.0 and 4.0×10^8 at/g (Figure 6), whereas older floodplains and terraces either have concentrations larger than 4.0×10^8 at/g in the vertical profile (sites F3, F10, and F11) or exhibit the inverted profile as seen at sites F7, F8, and F13, indicating previous stripping of ^{10}Be-rich topsoil. All of the floodplain samples were at or below the level of detection for ^{210}Pb and ^{137}Cs.

Several of the ^{10}Be floodplain profiles provide additional information. For example, sample site F1 was collected directly from a 2010 flood deposit on the main stem Root River. This sample contained no meteoric ^{210}Pb or ^{137}Cs and had a ^{10}Be concentration of 2.99×10^8 at/g, providing a constraint on the geochemical composition of watershed-integrated, modern flood deposits. Two other uniform depth profiles exhibiting relatively low ^{10}Be concentrations (3.5×10^8 at/g) are found at sites F4 and F5. While sampling site F4 (a 3-m-cutbank on South Branch) we found a belt with an attached buckle interbedded within the stratigraphy of the floodplain. The belt was buried 1.5 m from the surface and 0.5 m from the exposed face of the cut bank. On the back of the belt buckle was a copyright date of 1979, providing a maximum age constraint for when this surface was constructed by the river. Notably, the ^{10}Be concentrations here are again uniform through the profile with concentrations on the order of 3.5×10^8 at/g. Lead-210 and ^{137}Cs concentrations are again zero or negligible, indicating that the river has been transporting mostly ^{210}Pb- and ^{137}Cs-depleted sediment over the past thirty years while this surface has been constructed.

Sample location F5 is from the incised banks of Mill Creek, a tributary to the North Branch of the Root River. At this location, Mill Creek is incised through an old mill pond near Chatfield, Minnesota. This deposit is similar to the surfaces described by Walter and Merritts (2008) and is estimated by a local historian to have filled in nearly 100 years ago (J. Broberg, personal communication, 7 October 2010). The mill dam was recently removed and the stream has begun to evacuate sediment stored behind the dam. Stream banks are cohesive and steep and are rarely overtopped, even after high-intensity rainfall events. The uniform ^{10}Be concentration at this site indicates that sediment was sourced from similar landscape features and based on the concentrations in the profile; sediment trapped by the old

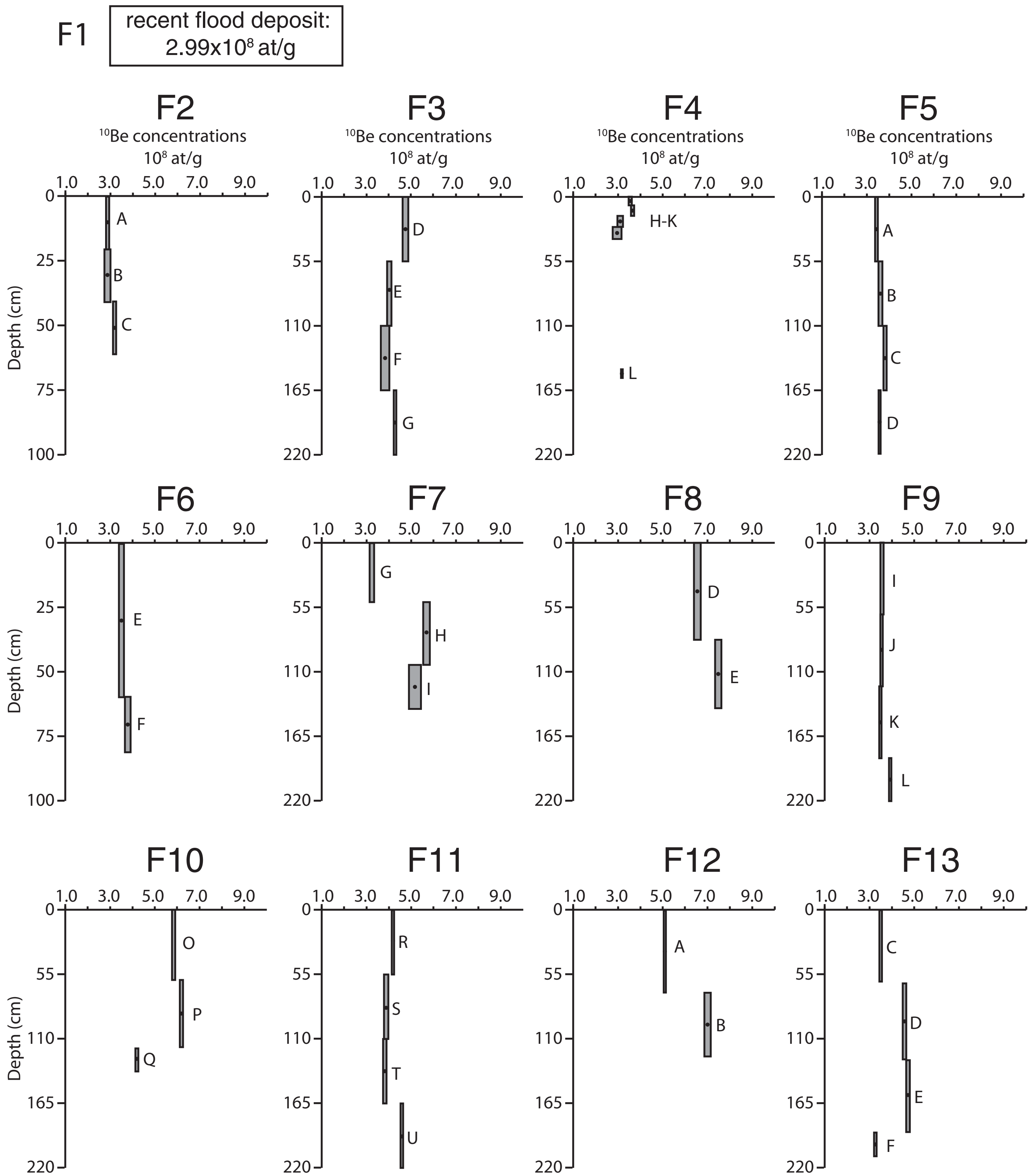

Figure 6. Beryllium-10 concentration profiles in floodplain cores and samples. F indicates that the sample was taken from a floodplain. Note that sample F14 is not a floodplain sample but a sample taken from an agricultural field in the glaciated region of the watershed. Although not labeled, sample locations are shown by red stars in Figure 1.

mill dam recorded the erosion of ^{10}Be-depleted soil from the uplands.

Beryllium-10 results from Crystal Creek (tributary to the South Branch; Figure 6, samples F6 and F7) are interpreted as follows. Elevated erosion rates during land conversion in the late 1800s and early 1900s stripped a significant amount of sediment from the upland areas, most likely from areas that were being converted from grasslands into agricultural fields. A portion of eroded sediment was deposited in the floodplain (site F7), which indicates that Crystal Creek was transporting washload with an average ^{10}Be concentration of about 5.5×10^8 at/g. Concentrations of the two lower samples in the profile of F7 are interpreted as stripped soil derived from agricultural fields. As a result of soil stripping and plowing, ^{10}Be concentrations in upland (agricultural fields) soils became depleted and washload ^{10}Be concentrations decreased to present-day concentrations measured from edge-of-field samplers (2.5×10^8 at/g). The surface sample from floodplain core F7 (sample G) is representative of the current sediment sources and water regime, as this location is inundated by medium to large floods. The inverted ^{10}Be profile has developed over time as a result of stripping the ^{10}Be-rich soils followed by erosion of ^{10}Be-depleted sediments.

Samples collected from a floodplain core taken near the Crystal Creek channel (F6) exhibit a uniform depth profile consistent with what we see in transport today (3.3×10^8 at/g). As stated earlier, sediment collected at the edge-of-field samplers indicates that source sediment from agricultural fields is 2.5×10^8 at/g. Suspended sediment samples collected on Crystal Creek have an average concentration of 3.3×10^8 at/g. Although tracer concentrations between the edge-of-field samples and suspended sediment samples collected at the outlet of the subwatershed are similar, contributions from forested hillslopes could also be responsible for increasing tracer concentrations from 2.5 to 3.3×10^8 at/g. Using a simple two end-member unmixing model, we back-calculated the range of proportions that each source area could contribute to result in the measured concentrations in the suspended sediment. Equation 2 was used to back-calculate the possible contributions from each of the three sources, where C_{ss} is the concentration of tracers measured in the suspended sediment, P is the percentage contributed from each source area, C is the concentration of tracers in the source area, and f, h, and fp represent each of the source areas (fields, hillslopes, and floodplains).

$$C_{ss} = \left(P_f * C_f\right) + \left(P_h * C_h\right) + \left(P_{fp} * C_{fp}\right). \qquad (2)$$

We assume only three possible sources contributing suspended sediment, so from these three sources, the contributions must make up 100 percent of the sample. From 5,151 possible combinations of our three source areas, only 10 result in the target concentration measured in the suspended sediment, indicating that hillslopes are likely contributing 0 to 20 percent, fields range from 60 to 80 percent, and floodplains contribute 0 to 40 percent.

The profiles of floodplain cores F6 and F7 support our hypothesis that rapid erosion associated with land conversion stripped sediment with high ^{10}Be concentrations, thus depleting tracer concentration in the source areas. This stripping resulted in ^{10}Be-depleted sediment currently being sourced from agricultural fields, which comprises the dominant sediment source in Crystal Creek, contrary to samples collected downstream in the system, which indicate predominance of near-channel sources.

Relative Contributions to Suspended Sediment Flux

The Root River watershed is a diverse landscape that has experienced differing erosion rates due to land use, hydrology, and geomorphic evolution. Because of the diversity in these factors, we expected to see much variation in the concentration of source area fingerprints. Fingerprinting results from source areas generally agree with expectations, although the results indicate that that there is a distinct difference between hillslopes and agricultural fields. Figure 7 compiles suspended sediment and source area samples throughout the entire watershed. Bars on source area concentrations represent the entire range of concentrations (min to max) measured for the respective source area, not standard deviation or error. Results indicate that hillslopes (large black square) have high concentrations of ^{10}Be and ^{210}Pb/^{137}Cs, but there is a large amount of variability on both axes. Agricultural field fingerprints (open square) tend to have a large range of ^{10}Be and ^{210}Pb/^{137}Cs, exhibiting some overlap with hillslope samples. Finally, floodplains (open triangle along x axis) have a large range of ^{10}Be concentrations, as discussed earlier, and contain little to no ^{210}Pb or ^{137}Cs.

Figure 7A includes suspended sediment samples from the entire Root River watershed (small open circles), each representing a sample collected during a storm event. The majority of suspended sediment concentrations overlap with ^{10}Be and ^{210}Pb concentrations measured in agricultural fields and modern floodplains. Very few suspended sediment samples exhibit ^{10}Be

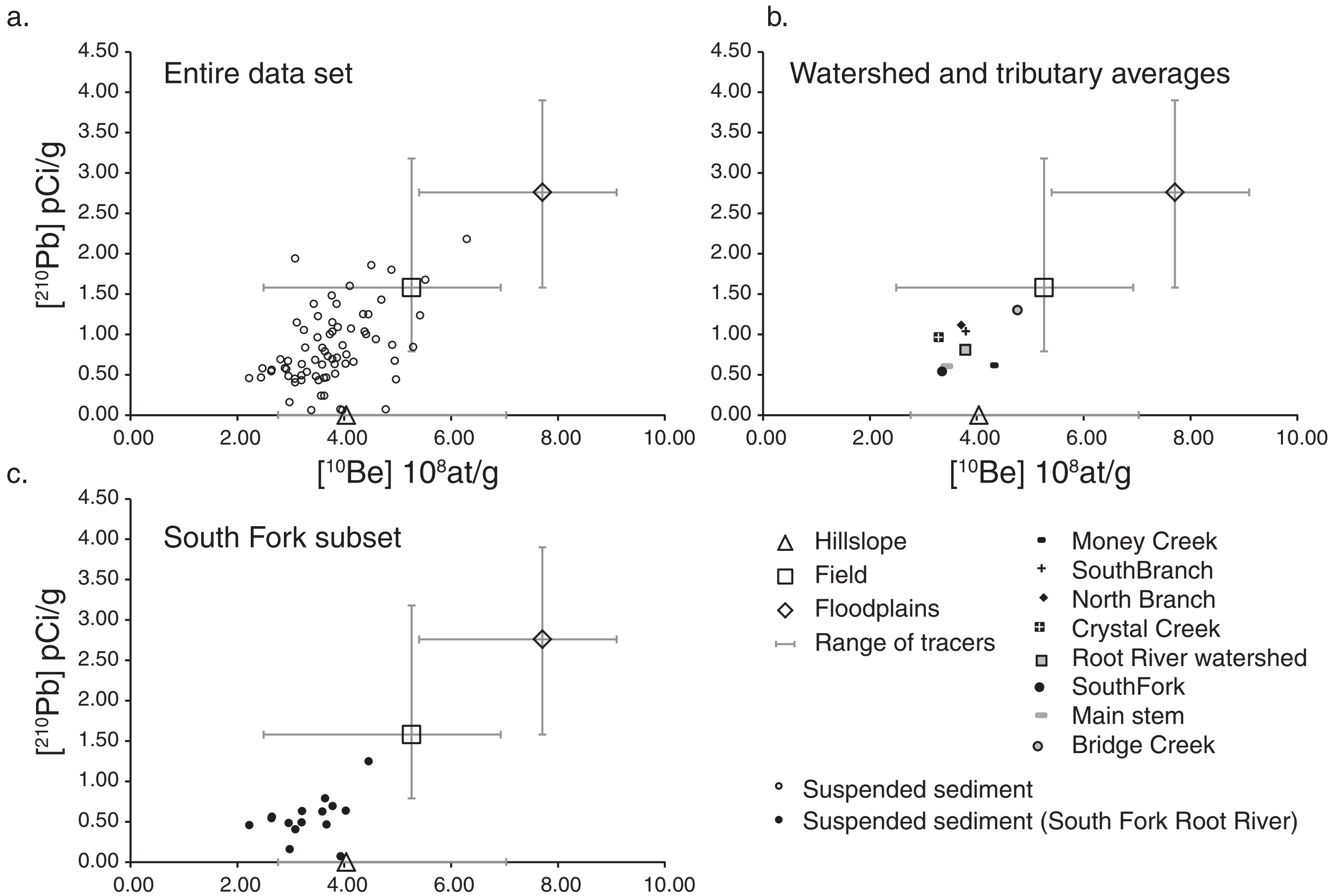

Figure 7. Plots showing suspended sediment fingerprinting results. Note that bars are ranges of tracer concentrations in the samples, not error bars on measurements. (A) The entire range of suspended sediment samples in relation to the ranges of tracer concentrations measured in the source areas. (B) Average tracer concentrations in each of the subwatersheds. On average, sediment is sourced from agricultural fields and tracers are diluted via exchange with bank sediments. (C) Example of sediment fingerprinting results from South Fork of the Root River. Data indicate that the majority of the sediment is being sourced from near-channel areas.

concentrations that overlap with even the lowest concentrations measured on hillslopes, indicating that hillslopes are not significant contributors to the modern suspended sediment flux at the watershed scale. Further, suspended sediment samples contain approximately 45 percent of the agricultural field ^{210}Pb concentrations on average. So although the overlap in ^{10}Be concentrations indicates that the vast majority of sediment originates from agricultural fields, the depleted concentrations of short-term tracers indicate that the majority of this sediment is not sourced directly from fields but, rather, is being reworked following long-term (more than seventy-five years) storage in the floodplains.

The fact that none of the tracer concentrations associated with suspended sediment samples fall outside the ranges observed in source areas suggests that we have adequately constrained the geochemical signature of our source areas. Despite our rigorous sampling campaign, however, we have not yet adequately constrained the standard error of the mean geochemical signature for each source type, and we therefore refrain from using a formal unmixing model to attribute sources of suspended sediment quantitatively.

At the watershed scale, variability in source area tracer concentrations is significant, as evidenced in Figure 7A. A more focused analysis considering only the South Fork of the Root River provides a clearer picture at that smaller scale. Of all the tributary sampling locations, the South Fork watershed contains the highest number of source area samples (n = 5) and exhibits the least amount of variance in source area tracer concentrations. Prior to evaluating fingerprinting results, observed geomorphic indicators led us to hypothesize that near-channel sources likely dominated the sediment contributions. The distribution of bank heights for the South Fork (Figure 3C) indicates that nearly

80 percent of the river is lined by banks in excess of 2 m tall. Many of these eroding cutbanks are higher in elevation relative to the depositing bank. An extreme example is found near the mouth of the South Fork, where the river is cutting into an 18-m tall bank, likely a Pleistocene outwash terrace, but only depositing a bank nearly 2 m on the opposite side.

Fingerprinting results support our hypothesis that this subwatershed is dominated by near-channel sources. Figure 7B is subset of the data shown in Figure 7A, containing only data from the South Fork. Each source area is depicted by large symbols with bars indicating the full range of tracer concentrations (^{10}Be and ^{210}Pb) in source areas. Suspended sediments (round filled circles) were collected near the mouth of the South Fork. There is a large range of ^{10}Be concentrations associated with sediment derived from forested hillslopes and agricultural fields, indicating that suspended sediment could likely have a similar range of tracer concentrations. It is noteworthy, though, that the ^{10}Be concentrations overlap exclusively with the agricultural fields and not the forested hillslopes, suggesting that the agricultural fields are the ultimate source of sediment (although recall that ^{10}Be is relatively insensitive to temporary floodplain storage). Comparing only the ^{210}Pb concentrations, which are sensitive to long-term floodplain storage, we conclude that 20 to 40 percent of suspended sediment is derived directly from agricultural fields and the river sources 60 to 80 percent of the suspended sediment from near-channel sources (i.e., the geochemical signature of suspended sediment is skewed toward that of floodplains rather than agricultural fields). Thus, the ^{10}Be concentrations indicate that agricultural fields have been the dominant source of sediment in the long term, and ^{210}Pb concentrations indicate that the eroded agricultural sediment has been stored and is currently being reworked from near-channel floodplains and terraces.

Conclusion

This work provides valuable information as to current and potential sources contributing to the sediment yield of the Root River. The combined use of the terrace map and the subwatershed fingerprinting results will help direct future research and management efforts, indicating areas that might be contributing sediment via bank erosion as areas to be first addressed for sediment reduction tactics. Alternatively, the data sets will help management realign expectations regarding sediment loads in the river and allow the river to work its way through these deposits. The combination of all lines of evidence provides answers to our key questions.

Where Is the Fine Sediment Coming From?

Analysis of the geomorphology and hydrology of the watershed in combination with fingerprinting results demonstrate that the three major sediment sources to the Root River are hillslopes, agricultural fields, and floodplains. There is a systematic pattern in ^{10}Be concentrations in all source areas dictated by the evolution of the landscape. Hillslopes have the highest concentrations of all three tracers. Valley fills, which were partly derived from glacial outwash but more recently capped with postsettlement alluvium, exhibit a range of ^{10}Be concentrations. Many of these floodplains and terraces record rapid stripping of agricultural soils (evident from ^{10}Be concentrations) occurring more than seventy years ago (evident from depleted ^{210}Pb and ^{137}Cs concentrations). Our best estimate of modern sediment composition comes from sample F14 (Figure 6), from edge-of-field samples, and from suspended sediment samples. Tracer concentrations associated with suspended sediment indicate that agricultural fields have contributed the dominant proportion of sediment over the past 150 years since settlement, but the majority of suspended sediment in the river today has experienced storage in, and has recently been reworked from, floodplains and alluvial terraces.

Recent reports from the U.S. Department of Agriculture (USDA) suggest that with rising corn prices, an estimated 97.3 million acres of corn is expected to be planted throughout the United States, the highest planted acreage since 1936 when an estimated 102 million acres were planted. In Minnesota this represents an estimated increase of 3 percent from 2012 (USDA 2013). Much of this increase in planting could occur on marginal lands that are more vulnerable to erosion (and were therefore historically prime locations for conservation), which has the potential to again increase the amounts of sediment eroded from agricultural fields.

What Proportions of the Sediment Are from Upland Versus Near-Channel Erosion?

The data sets illustrated in Figure 7 demonstrate that local variability in historic erosion of source areas can cause highly variable tracer concentrations in source fingerprints. Such variability can induce scatter in the suspended sediment tracer concentrations, obscuring trends and making source attribution challenging. Nevertheless, useful information can be gleaned from the broader patterns, specifically that ^{10}Be concentrations associated with suspended sediment almost exclusively fall within the range of agricultural fields rather than forested hillslopes and the fact that much of the suspended sediment in transport appears to have been stored in, and is currently being sourced from, floodplains, as evidenced by depleted ^{210}Pb and ^{137}Cs concentrations.

When applied at a subwatershed scale, more obvious trends and interpretable patterns emerge, suggesting that quantitative source apportionment is more appropriate on the scale of subwatersheds where local source fingerprints can be matched to local suspended sediment concentrations. As scale increases, we observed a shift in sediment sources. Sediment source apportionment in Crystal Creek (48 km^2) indicates agricultural fields as the dominant source. In contrast, source apportionment in the South Fork (736 km^2) indicates floodplains and near-channel sources as dominant. Results from the mapping terraces and floodplains along the river, in combination with the observed shift in hydrology over the several decades, reinforce our conclusions that near-channel sources are currently the dominant supplier of excess sediment in the Root River.

How Much of the Excess Sediment Loading Is Caused by Modern Land Use and Water Management Versus the Legacy of Past Land Use?

The Root River is a dynamic and heterogeneous system that has experienced variable erosion rates and patterns across the landscape. Historic flow data indicate a shift in hydrologic regime over the last two to three decades. Geomorphic analysis provides evidence of likely sediment sources, and sediment fingerprinting results constrain the relative contribution of sources over three years that cover the range of high to low flows. We document the variability of upland fingerprints as well as systematic variability in floodplain ^{10}Be depth profiles. Short-lived geochemical tracer concentrations in suspended sediment indicate that storage in the floodplains plays a large role in how this sediment is routed through the system. Floodplains and terraces, which are prominent throughout the watershed and have been strongly influenced by past land use, are the dominant source if the watershed is considered as a whole. We document, though, that contemporary sediment contributions directly from agricultural fields can dominate at smaller scales (e.g., Crystal Creek), particularly in the upper parts of the watershed. Past land use and geomorphic setting established the template for near-channel sediment storage, and modern land use and hydrology are accelerating erosion of these near-channel sources.

Taken together, our results provide critical insight into how sediment predictions should be made for relatively large, complex watersheds. Conventional USLE-based estimates are useful for identifying local erosional hotspots, but USLE-based approaches are inherently limited at the larger watershed scale by the a priori assumption that the contemporary sediment yield is directly attributable to erosion ongoing in the upland environment (hillslopes and agricultural fields). Hence, such terrestrial erosion models could be calibrated to more or less match the suspended sediment flux observed at the mouth of the watershed, thus leading to an erroneous, if potentially convincing, argument that sediment sources are being adequately simulated. Our detailed analysis here, however, illustrates that the actual story is more complicated. Given the pervasive human perturbations in agricultural landscapes and extensive legacy sediment that has been observed in this study and elsewhere, combined with pervasive shifts in hydrology that have been observed here and elsewhere, the a priori assumption that modern sediment sources are dominated by terrestrial erosion (which USLE and its derivatives predict relatively accurately at the local scale) should be applied with caution. Multiple, complementary lines of information, such as those explored here, are essential for developing an understanding of watershed sediment dynamics on which management and policy decisions can be based.

Supporting Data

The raw fingerprinting data are available upon request from the corresponding author.

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References

Beach, T. 1994. The fate of eroded soil: Sediment sinks and sediment budgets of agrarian landscapes in southern Minnesota, 1851–1988. *Annals of the Association of American Geographers* 84:5–28.

Belmont, P., K. B. Gran, S. P. Schottler, P. R. Wilcok, S. S. Day, C. Jennings, J. W. Lauer, et al. 2011. Large shift in source of fine sediment in the Upper Mississippi River. *Environmental Science & Technology* 45:8804–10.

Birkinshaw, S. J., and J. C. Bathurst. 2006. Model study of the relationship between sediment yield and river basin area. *Earth Surface Processes and Landforms* 31:750–61.

Boomer, K. B., D. E. Weller, and T. E. Jordan. 2008. Empirical models based on the universal soil loss equation fail to predict sediment discharges from Chesapeake Bay catchments. *Journal of Environmental Quality* 37:79–89.

Burt, T. P., and R. J. Allison. 2010. *Sediment cascades in the environment: An integrated approach*. Hoboken, NJ: Wiley.

Chmeleff, J., F. von Blanckenburg, K. Kossert, and D. Jakob. 2010. Determination of the 10Be half-life by multicollector ICP-MS and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 268: 192–99.

Collins, A. L., D. E. Walling, and G. J. L. Leeks. 1997. Fingerprinting the origin of fluvial suspended sediment in larger river basins: Combining assessment of spatial provenance and source type. *Geografiska Annaler: Series A, Physical Geography* 79:239–54.

de Vente, J., J. Poesen, M. Arabkhedri, and G. Verstraeten. 2007. The sediment delivery problem revisited. *Progress in Physical Geography* 31:155–78.

Dogwiler, T. 2010. *Rush-Pine Creek Watershed preliminary assessment and scoping plan*. Winona, MN: Southeastern Minnesota Water Resources Center, Winona State University.

ESRI. 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute.

Field, C. V., G. A. Schmidt, D. Koch, and C. Salyk. 2006. Modeling production and climate-related impacts on 10Be concentration in ice cores. *Journal of Geophysical Research* 111:D15107.

Finnegan, N. J., and W. E. Dietrich. 2011. Episodic bedrock strath terrace formation due to meander migration and cutoff. *Geology* 39:143–46.

Fryirs, K. A., G. J. Brierley, N. J. Preston, and M. Kasai. 2007. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *CATENA* 70:49–67.

Gellis, A. C., and D. E. Walling. 2011. Sediment source fingerprinting (tracing) and sediment budgets as tools in targeting river and watershed restoration programs. In *Stream restoration in dynamic fluvial systems: Scientific approaches, analyses, and tools*, ed. A. Simon, S. J. Bennett, and J. M. Castro, 263–91. Washington, DC: AGU.

Gran, K. B., N. Finnegan, A. L. Johnson, P. Belmont, C. Wittkop, and T. Rittenour. 2011. Landscape evolution in south-central Minnesota and the role of geomorphic history on modern erosional processes. *GSA Today* 21:7–9.

Heikkilä, U. 2007. Modeling of the atmospheric transport of the cosmogenic radionuclides ^{10}Be and ^{7}Be using the ECHAM5-HAM general circulation model. PhD thesis, ETH-Zurich, Switzerland.

Knox, J. C. 1977. Human impacts on Wisconsin stream channels. *Annals of the Association of American Geographers* 67:323–42.

———. 2001. Agricultural influence on landscape sensitivity in the Upper Mississippi River Valley. *CATENA* 42:193–224.

———. 2006. Floodplain sedimentation in the Upper Mississippi Valley: Natural versus human accelerated. *Geomorphology* 79:286–310.

Lauer, J. W., and G. Parker. 2008. Net local removal of floodplain sediment by river meander migration. *Geomorphology* 96:123–49.

Lauer, J. W., and J. Willenbring. 2010. Steady state reach-scale theory for radioactive tracer concentration in a simple channel/floodplain system. *Journal of Geophysical Research* 115:F04018.

Lindstrom, M. J., W. W. Nelson, and T. E. Schumacher. 1992. Quantifying tillage erosion rates due to moldboard plowing. *Soil and Tillage Research* 24:243–55.

Lueth, R. A. 1984. *Soil survey of Houston County, Minnesota*. Washington, DC: Soil Conservation Service.

Mackin, J. H. 1948. Concept of the graded river. *Geological Society of America Bulletin* 59:463–512.

Macklin, M. G. K. A. Hudson-Edwards, and E. J. Dawson. 1997. The significance of pollution from historic metal mining in the Pennine orefields on river sediment contaminant fluxes to the North Sea. *Science of the Total Environment*, 194–195, 391–397.

Marks, J. B. 1942. Land use and plant succession in Coon Valley, Wisconsin. *Ecological Monographs* 12:113–33.

Martin, J. M., and M. Meybeck. 1979. Elemental mass-balance of material carried by major world rivers. *Marine Chemistry* 7:173–206.

Masarik, J., and J. Beer. 2009. An updated simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere. *Journal of Geophysical Research* 114:D11103.

Minnesota Pollution Control Agency (MPCA). 2010. Minnesota's impaired waters and TMDLs. 2010 Draft TMDL List. http://www.pca.state.mn.us/index.php/water/water-types-and-programs/minnesotas-impaired-waters-and-tmdls/assessment-and-listing/303d-list-of-impaired-waters.html

Montgomery, D. R. 2007. Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences* 104:13268–72.

Naden, P. S. 2010. The fine-sediment cascade. In *Sediment cascades*, ed. T. Burt and R. Allison, 271–305. Hoboken, NJ: Wiley.

Noller, J. S. 2000. Lead-210 geochronology. In *Quaternary geochronology: Methods and applications*, ed. J. S. Noeller, J. M. Sowers, and W. R. Lettis, 115–20. Washington, DC: AGU.

Owens, P. N., D. E. Walling, and Q. He. 1996. The behaviour of bomb-derived caesium-137 fallout in catchment soils. *Journal of Environmental Radioactivity* 32:169–91.

Palmer, M. A., A. P. Covich, S. A. M. Lake, P. Biro, J. J. Brooks, J. Cole, C. Dahm, et al. 2000. Linkages between aquatic sediment biota and life above sediments as potential drivers of biodiversity and ecological processes. *BioScience* 50:1062–75.

Parsons, A. J., and I. D. L. Foster. 2011. What can we learn about soil erosion from the use of ^{137}Cs? *Earth-Science Reviews* 108:101–13.

Pazzaglia, F. J. 2013. 9.22 Fluvial terraces. In *Treatise on geomorphology*, ed. F. S. John, 379–412. San Diego, CA: Academic Press.

Pelletier, J. D. 2012. A spatially distributed model for the long-term suspended sediment discharge and delivery ratio of drainage basins. *Journal of Geophysical Research* 117:F02028.

Phillips, J. D. 2006. Evolutionary geomorphology: Thresholds and nonlinearity in landform response to environmental change. *Hydrology and Earth System Sciences Discussions* 3:365–94.

Pigati, J. S., and N. A. Lifton. 2004. Geomagnetic effects on time-integrated cosmogenic nuclide production with emphasis on in situ 14C and 10Be. *Earth and Planetary Science Letters* 226:193–205.

Renard, K. G., G. R. Foster, G. A. Weesies, D. K. McCool, and D. C. Yoder. 1997. *Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE)*. Washington, DC: U.S. Government Printing Office.

Schockel, B. H. 1917. Settlement and development of the lead and zinc mining region of the driftless area with special emphasis upon Jo Daviess County, Illinois. *The Mississippi Valley Historical Review* 4:169–92.

Schottler, S. P., J. Ulrich, P. Belmont, R. Moore, J. W. Lauer, D. R. Engstrom, and J. E. Almendinger. 2013. Twentieth century agricultural drainage creates more erosive rivers. *Hydrological Processes*. doi: 10.1002/hyp.9738.

Sequoia. 2011. *LISST-Portable user's guide, version 3.11*. Bellevue, WA: Sequoia Scientific Inc.

Smith, S. M. C., P. Belmont, and P. R. Wilcock. 2011. Closing the gap between watershed modeling, sediment budgeting, and stream restoration. In *Stream restoration in dynamic fluvial systems: Scientific approaches, analyses, and tools*, ed. A. Simon, S. J. Bennett, and J. M. Castro, 293–317. Washington, DC: AGU.

Soil and Water Conservation Society. 2003. *Conservation implications of climate change: Soil erosion and runoff from cropland*. Ankeny, IA: Soil and Water Conservation Society.

Stout, J., and P. Belmont. 2013. TerEx Toolbox for semi-automated selection of fluvial terrace and floodplain features from lidar. *Earth Surface Processes and Landforms*. doi: 10.1002/esp.3464

Surber, T. 1924. *A biological reconnaissance of the Root River drainage basin southeastern Minnesota*. St. Paul: Minnesota State Game and Fish Department.

Syverson, K. M., and P. M. Colgan. 2004. The Quaternary of Wisconsin: A review of stratigraphy and glaciation history. In *Developments in quaternary sciences*, ed. J. Ehlers and P. L. Gibbard, 295–311. New York: Elsevier.

Syvitski, J. P. M., C. J. Vorosmarty, A. J. Kettner, and P. Green. 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* 308:376–80.

Trimble, S. W. 1999. Decreased rates of alluvial sediment storage in the Coon Creek Basin, Wisconsin, 1975–93. *Science* 285:1244–46.

Trimble, S. W., and P. Crosson. 2000. U.S. soil erosion rates: Myth and reality. *Science* 289:248–50.

U.S. Department of Agriculture (USDA). 2013. *Prospective plantings*. Washington, DC: National Agricultural Statistics Service, U.S. Department of Agriculture.

U.S. Environmental Protection Agency (EPA). 2012. *Water quality assessment and TMDL information*. Washington, DC: U.S. Environmental Protection Agency. http://iaspub.eda.gov/waters10/attains_nation_cy.control

University of Wisconsin–Madison. 1990. *Original vegetation cover of Wisconsin*. Madison: Wisconsin Department of Natural Resources.

Viparelli, E., J. W. Lauer, P. Belmont, and G. Parker. 2013. A numerical model to develop long-term sediment budgets using isotopic sediment fingerprints. *Computers & Geosciences* 53:114–22.

Walling, D. E. 1983. The sediment delivery problem. *Journal of Hydrology* 65:209–37.

———. 2005. Tracing suspended sediment sources in catchments and river systems. *Science of the Total Environment* 344:159–84.

Walling, D. E., and Q. He. 1998. The spatial variability of overbank sedimentation on river floodplains. *Geomorphology* 24:209–23.

Walling, D. E., and B. W. Webb. 1996. Erosion and sediment yield: A global review. In *Erosion and sediment yield: Global and regional perspectives*, ed. D. E. Walling and B. W. Webb, 3–19. Exeter, UK: IAHS.

Walter, R. C., and D. J. Merritts. 2008. Natural streams and the legacy of water-powered mills. *Science* 319:299–304.

Willenbring, J. K., and F. von Blanckenburg. 2010. Meteoric cosmogenic Beryllium-10 adsorbed to river sediment and soil: Applications for Earth-surface dynamics. *Earth-Science Reviews* 98:105–22.

Wischmeier, W. H., and D. D. Smith. 1978. *Predicting rainfall erosion losses—A guide to conservation planning*. Washington, DC: U.S. Department of Agriculture.

Correspondence: The University of Melbourne, Department of Resource Management and Geography, 221 Bouverie Street, Carlton, Victoria, Australia 3053, e-mail: justinstout82@gmail.com (Stout); Utah State University, Department of Watershed Sciences, 5210 Old Main Hill NR 210, Logan, UT 84322, e-mail: patrick.belmont@usu.edu (Belmont); St. Croix Watershed Research Station, 16910 152nd St. North Marine, St. Croix, MN 55047, e-mail: schottler@smm.org (Schottler); University of Pennsylvania, Department of Earth and Environmental Science, 240 S. 33rd Street, Philadelphia, PA 19104, e-mail: jane.willenbring@sas.upenn.edu (Willenbring).