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Legacy sediment: Definitions and processes of episodically produced anthropogenic sediment

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ABSTRACT

Extensive anthropogenic terrestrial sedimentary deposits are well recognized in the geologic literature and are increasingly being referred to as *legacy sediment* (LS). Definitions of LS are reviewed and a broad but explicit definition is recommended based on episodically produced anthropogenic sediment. The phrase is being used in a variety of ways, but primarily in North America to describe post-settlement alluvium overlying older surfaces. The role of humans may be implied by current usage, but this is not always clear. The definition of LS should include alluvium and colluvium resulting to a substantial degree from a range of human-induced disturbances; e.g., vegetation clearance, logging, agriculture, mining, grazing, or urbanization. Moreover, LS should apply to sediment resulting from anthropogenic episodes on other continents and to sediment deposited by earlier episodes of human activities.

Given a broad definition of LS, various types of LS deposits are described followed by a qualitative description of processes governing deposition, preservation, and recruitment. LS is deposited and preserved where sediment delivery (D_S) exceeds sediment transport capacity (T_C). This can be expressed as a *storage potential ratio* that varies within and between basins and through time. When $D_S/T_C < 1$, recruitment and transport of LS dominate, but if $D_S/T_C > 1$, deposition and preservation are likely. When $D_S/T_C \gg 1$, abundant deposition and graded deposits are likely even without barriers or sinks. Thus, spatial patterns of LS deposits may reveal information about past land-use history and hydrodynamics in a catchment.

1. Introduction

Anthropogenic sediment is an extremely important element of change during the Anthropocene. It drives lateral, longitudinal, vertical, and temporal connectivity in fluvial systems. It provides evidence of the history and geographic locations of past anthropogenic environmental alterations, the magnitude and character of those changes, and how those changes may influence present and future trajectories of geomorphic response. It may contain cultural artifacts, biological evidence of former ecosystems (pollen, macrofossils, etc.), or geochemical and mineralogical signals that record the sources of sediment and the character of land use before and after contact. Rivers are often dominated by cultural constructs with extensive legacies of anthropogeomorphic and ecologic change. A growing awareness of these changes is guiding modern river scientists to question if there is such a thing as a natural river (Wohl, 2001; Wohl and Merritts, 2007). Understanding anthropogeomorphic change goes well beyond an academic question because it bears upon basic decisions in river restoration, water quality regulations, aquatic ecosystem management, sediment budgets, flood-risk management, and long-term geomorphic trajectories.

Recognition of the tremendous contributions of anthropogenic sediment to modern sediment budgets by early geomorphologists (Gilbert, 1917; Happ et al., 1940; Knox, 1972) led to a fundamental reconsideration of sediment sources in many fluvial environments. Theories of sediment delivery and storage that blossomed in the 1970s, coupled with the recognition of massive loadings of anthropic sediment, lead to the inescapable conclusion that many fluvial systems are highly dynamic and not in equilibrium with regards to a balance between sediment loads and transport capacity (Trimble, 1977). For example, high sediment loadings in streams of the Atlantic Coastal Plain of the northeastern USA are better explained by recruitment of anthropogenic sediment from floodplains and terraces than by intensive upland land use (Walter and Merritts, 2008; Wohl and Rathburn, 2013). The awareness of anthropogenic sediment has a long history, although the deposits have been referred to by various names. In many regions of North America, sedimentary deposits were produced by accelerated erosion associated with intensive land clearance and agriculture

Abbreviations: LS, legacy sediment; SDR, sediment delivery ratio; PSA, post settlement alluvium.

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following EuroAmerican settlement (Happ et al., 1940; Happ, 1945; Knox, 1972, 1977, 1987, 2006; Trimble, 1974; Costa, 1975; Magilligan, 1985; Jacobson and Coleman, 1986; Faulkner, 1998; Lecce and Pavlowsky, 2001; Florsheim and Mount, 2003; Jackson et al., 2005; Walter and Merritts, 2008; Gellis et al., 2009; Merritts et al., 2011; Hupp et al., 2013). Mining also generated large sedimentation events in North America (Gilbert, 1917; Knox, 1987; James, 1989; Leigh, 1994; Lecce, 1997; Stoughton and Marcus, 2000; Marcus et al., 2001; Bain and Brush, 2005; Lecce et al., 2008). These anthropogenic deposits are being increasingly referred to as '*legacy sediment*' (LS) by environmental scientists.

Anthropogenic sediment does not occur uniformly over the landscape but collects in certain locations where it creates landforms. Types of LS deposits vary greatly from colluvial drapes on hill sides, to aprons and fans at the base of hill slopes, to a variety of alluvial depositional features in channels, floodplains, deltas, lakes, and estuaries. ('Colluvium' is used broadly in this paper to include mass wasting as well as sheetflow and rill deposits on or at the base of hillslopes (Fairbridge, 1968). It does not necessarily connote anthropogenically produced sediment (LS) as may be implied in central Europe (Leopold and Völkel, 2007).) A typology of LS is described based on locations and geomorphology of deposits. Explanations for heterogeneous spatial patterns of LS deposits are given based on differences in sediment production, transport capacity, accommodation space in valley bottoms, and other factors that are intrinsically geomorphic. An explanation is presented for the processes that govern sediment storage potential, delivery ratios, and lateral, longitudinal, and temporal connectivity. These concepts are essential to understanding why anthropogenic sediment is located where it is, how it behaved over the Anthropocene, and how it may behave in the future.

2. Use and definitions of 'legacy sediment'

2.1. Increasing use

The concept of inheriting a legacy from the past is pervasive in the environmental science literature, and LS is a logical outgrowth of that perspective. Over the first decade of the new millennium, the term, *legacy sediment* (LS) began to be used with increasing frequency in a variety of contexts. A partial Internet sample of published scientific papers or reports that contain the phrase '*legacy sediment*' indicates that use of the term has proliferated, especially in the eastern USA, and across a range of disciplines including geomorphology, hydrology, ecology, environmental toxicology, and planning (Table 1). The earliest occurrence of the term was in 2004 and was concerned with the effects of copper contamination from legacy sediment on water quality (Novotny, 2004). By 2007, LS had appeared in several studies of historical alluvium in the eastern USA. The use of LS to describe historical floodplain alluvium increased greatly with the findings of legacy mill-pond surveys in Pennsylvania, USA (Walter and Merritts, 2008; Merritts et al., 2011). Although these two publications do not use the phrase, it was used by the authors and others as early as 2005 in abstracts and field trip logs in association with sediment trapped in legacy mill ponds. The use of 'legacy sediment' in publications grew at about the same time as the use of 'legacy contaminants' and 'legacy pollution.' An Internet search of publications with the phrases "legacy contam*" and "legacy pollut*" in Wiley Online and Science Direct indicate a much larger number of uses of those terms than LS, but a similar—perhaps slightly earlier—timing of rapid growth (Fig. 1).

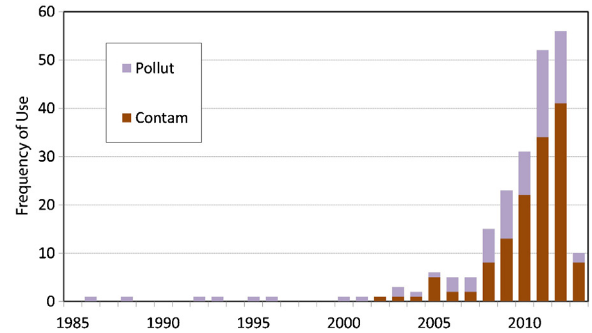

Fig. 1. Number of occurrences of "legacy pollut*" and "legacy contam*" occurring in samples from Internet searches of scientific publications. The frequency of these strings is much greater than "legacy sediment" (Table 1), and may begin slightly earlier, but rapid growth after 2005 is common to all.

The contexts in which LS is used in publications vary widely from sources of legacy contaminations in toxicological studies (Bay et al., 2012), to sediment budgets (Gellis et al., 2009), to fluvial geomorphic and ecological processes (Hupp et al., 2009). This paper examines questions of geographic location,

Table 1
An Internet sample of studies that refer to 'legacy sediment'.

Location	Context	Source
California	PSA	Canuel et al. (2009), Stein and Cadien (2009), Bay et al. (2012), Greenfield and Allen (2013)
Georgia	PSA	Schoonover et al. (2007), Neary et al. (2009), Mukundan et al. (2011)
Idaho	Logging, grazing, mining	Goode et al. (2012)
Kentucky	LU change	Russo and Fox (2012)
Maryland	PSA, Ag	Allmendinger et al. (2007), Weber and Allen (2010), Schenk et al. (2012)
Minnesota	PSA	Gran et al. (2011)
New Hampshire	PSA	Pearson et al. (2011)
North Carolina	PSA, Ag	Hupp et al. (2009), Clinton (2011), Riggsbee et al. (2012)
Ohio	LU change	Peck et al. (2007)
Pennsylvania	PSA	Walter et al. (2007), Galster et al. (2008), deWet et al. (2011), Schenk and Hupp (2009), Schenk et al. (2012), Niemitz et al. (2013)
South Carolina	PSA	James (2006, 2010)
Tennessee	LU change	Cowan et al., 2013
Virginia	PSA Ag	Hupp et al. (2013), Schenk et al. (2012)
Vermont	Deforestation	McBride et al. (2008)
Wisconsin	PSA	Fitzpatrick et al. (2010)
North America (*in passim*)	PSA	Novotny (2004), Trimble (2008)
California	Mining	James (2010)
North Carolina	Mining	Pavlowsky et al. (2010)
United Kingdom	LU change (post industrial)	Hale et al. (2010)

age, stratigraphic nomenclature, and genetic processes, in an attempt to clarify the concept of LS and avoid vague, obscure, or conflicting uses of the term. Ultimately, a definition of LS is suggested with broad applicability to sedimentary bodies generated by anthropogenic depositional episodes.

2.2. Initial definitions of LS

Much usage of the term LS has gone without an explicit definition and relies on preconceived understandings or implications that may vary between disciplines. The primary implied meanings apparently are the historical age or the anthropogenic origin of the sediment. One consideration in defining LS is to examine the etymology of legacy. 'Legacy' is defined by Merriam Websters dictionary as "something transmitted by or received from an ancestor or predecessor or from the past <the *legacy* of the ancient philosophers>"; i.e., an inheritance. Although this leaves open the possibility that "*legacy sediment*" simply refers to something from the past, all sediment results from past processes, so legacy sediment would be redundant in that sense. Thus, when the phrase LS is used without definition or contextual explanation, a more specific meaning is implied. In general, an anthropogenic origin may be implicit, given the definition of legacy as something 'from an ancestor or predecessor;' i.e., it may logically follow that human agency was involved. In this sense, and building upon recent usage of the term, LS resulted, at least in part, from anthropically accelerated sediment production. Although "legacy" has been used in different contexts to describe naturally produced sediment; e.g., a legacy of climate change, the phrase, LS, by itself should be used to imply that humans played a substantial role in the processes that generated the sediment.

Definitions that have been given for LS vary but usually indicate a post-colonial age of alluvium in North America (e.g., Niemitz et al., 2013). Many questions about the specific source, physical character, extent, or location of LS have not been addressed. For example, does the definition of LS apply narrowly to agriculturally derived alluvium, or does it include other land uses such as logging and mining? Does it include colluvium on hillslopes and fans? Is LS defined by its lithologic or chronologic characteristics? If LS is a lithologic unit, is it restricted to the anthropogenic component of the sediment or is the diluted mass considered to be a LS deposit as a whole? Since LS is usually mixed with sediment from other sources, what proportion of anthropogenic sediment is required for the deposit to be considered LS? Or how intensive must land-use change have been in how much of the catchment? If LS is a chronologic unit that begins with the onset of settlement, does it stop being formed with primary deposition, or does it continue to propagate through reworking? Is there a minimum thickness to LS or are areas of deposits included that pinch out laterally or longitudinally? Is there a minimum extent? Specifying answers to all of these questions is not necessary for a broad concept of LS to be useful, but the questions demonstrate vagueness often associated with the present use of the term and the need for a definition that provides some clear constraints.

A Legacy Sediment Workgroup—established by the Pennsylvania Department of Environmental Protection (PDEP) to evaluate historical alluvium in Pennsylvania—generated two definitions of LS for use within the Pennsylvania regional context. The first definition is listed as 'generic' and is more broadly applicable to other areas:

> "Sediment that was eroded from upland hill slopes after the arrival of early Colonial American settlers and during centuries of intensive land uses; that was deposited in valley bottoms along stream corridors, burying pre-settlement streams, floodplains, wetlands, and valleys; and that altered and continues to impair the hydrologic, biologic, aquatic, riparian, and chemical functions of pre-settlement and modern environments. Legacy sediment often accumulated behind ubiquitous low-head mill dams and in their slackwater environments, resulting in thick accumulations of fine-grained sediment." PDEP Legacy Sediment Workgroup (nd)

While appropriate for the immediate task of the PDEP to describe historical alluvium along rivers in Pennsylvania, this definition contains specific constraints that limit the definition. A more specific 'technical definition' was also presented:

> Legacy Sediment (n.) Sediment that (1) was eroded from upland slopes during several centuries of intensive land clearing, agriculture, and milling (in the eastern U.S., this occurred from the late 17th to late 19th Centuries); (2) collected along stream corridors and valley bottoms, burying pre-settlement streams, floodplains, wetlands, and dry valleys; and that altered the hydrologic, biologic, aquatic, riparian, and chemical functions of pre-settlement streams and floodplains; (3) accumulated behind ubiquitous low-head mill dams in slackwater environments, resulting in thick accumulations of fine-grained sediment, which distinguishes "legacy sediment" from fluvial deposits associated with meandering streams; (4) can also accumulate as coarser grained, more poorly sorted colluvial (not associated with stream transport) deposits, usually at valley margins; (5) can contain varying amounts of total phosphorus and nitrogen, which contribute to nutrient loads in downstream waterways from bank erosion processes..." PDEP Legacy Sediment Workgroup (nd)

To interpret this definition assume that, as in dictionaries, each numbered item provides an alternate definition; that is, these can be interpreted as 'or' rather than 'and' conditions. Thus, the first point provides a broad category for agriculturally produced post-settlement alluvium. The second describes a set of lowland sites where LS is likely to be deposited, and the fourth definition includes colluvium. Although these definitions may work well for the region and purposes for which they were derived, they largely constrain the scope of LS to sediment produced by agriculture on hill slopes and deposited in lowlands during post-Colonial time in North America.

2.3. A broader definition

A more general definition of LS is needed for the various applications of the term that are emerging in the scientific literature. The definition should be flexible enough to include sediment produced by a range and mixture of anthropogenic activities that may have resulted in a wide variety of depositional sites, processes, and sedimentary structures and textures. First, the definition of LS should include human activities beyond agricultural clearance; i.e., lumbering, mining, road building, urbanization, and other land-use practices (Fig. 2). By including sediment from resource extraction activities such as mining and logging, this definition of LS may differ somewhat from some literal interpretations of *post-settlement alluvium* (PSA). Deposition from mining, lumbering, and other such activities may occur in extra-frontier outposts prior to or without settlement of a region, so LS may apply to anthropogenic deposits in addition to PSA. Given the difficulties of (1) determining the source of sedimentary materials, (2) the polygenetic histories of many deposits, and (3) complexities of isolating effects of climate change, thorough and precise identification of how sediment was produced should not be a sticking point as long as it is clear that the deposit is associated with processes substantially accelerated by human activities. The

Fig. 2. Braid-bar terraces of Shady Creek, California. This is a small creek that received large volumes of hydraulic gold mining sediment in the 19th century, aggraded, then incised. The white terrace sands and gravels are a legacy of mining. Photographed November, 2002 by author.

term has a logical potential to describe broad classes of anthropogenic sediment in a variety of environments and it is increasingly being used that way in the literature.

With regard to geomorphic forms and position on the landscape, LS deposits may progress through facies changes from rills and gullies, to cobble- and gravel-bed streams in steep valleys, to floodplains and channel fill along large rivers, to fine-grained deposits in slack-water environments. Definitions that attempt to separate one part of a facies can falter if changes are time transgressive or if channel morphogenesis has occurred. Different fluvial environments may dominate a site at different times during a depositional episode resulting in strata that represent multiple environments. For example, a meandering channel floodplain may be converted to a braided channel and revert back to a meandering channel all within a single period of settlement. A debris flow from a side valley may deposit coarse colluvium on top of laminated overbank silts leaving cobbles overlying fine-grained material in an historical section. Defining LS on the basis of a particular phase or environment of deposition can be problematic. Some definitions of LS have emphasized the impacts on modern fluvial systems (PDEP, nd; Niemitz et al., 2013). Although LS is often highly disruptive to environmental systems (Wohl and Rathburn, 2013) and this is very important in environmental management, substantial alterations to hydrologic, biologic, aquatic, riparian, and chemical functions should not be a defining condition for sediment to be classified as LS.

These factors, together with common usage of the term, provide the basis for a definition of LS as sedimentary deposits generated episodically by human activities:

> "Legacy sediment: Earth materials—primarily alluvium [or colluvium]—deposited following human disturbances such as deforestation, agricultural land use, or mining. The phrase is often used to describe post-European floodplain sediment, also known as post settlement alluvium. Awareness of legacy sediment has grown in response to the importance it plays in sediment budgets, water quality, river restoration, toxicity, lateral channel connectivity, and geomorphic theory..." (James, 2013, Glossary)

> "Legacy sediment is primarily alluvium [and colluvium] that was deposited following human disturbances in a watershed. The disturbance may have been in the form of deforestation, plowing agricultural land, mining, or other land-use changes. In North America and Australia, legacy sediments are ubiquitous and represent episodic erosion in response to the colonization of land by European settlers who introduced Old World land-clearance technologies (e.g. steel tools and plows pulled by draft animals) and export economies. In these settings, legacy sediments are often described as post-settlement alluvium (PSA), which may cover entire floodplains and bury the pre-settlement soil with a thick mantle of relatively young stratified sediment (Griffiths, 1979; Knox, 1972, 1977, 2006). (James, 2010, p. 588)

These definitions refer to the entire depositional body, not simply the anthropogenic portions of sediment within the deposit. LS deposits are deposited over a period of centuries but they are time transgressive because initiation as well as peak rates may occur at different times within a basin and at largely different times between regions. Production of LS may be polycyclic with multiple events over time, such as when failed mill dams or collapsed gully walls produce a second cycle of anthropogenic sediment. Thus, LS cascades may occur in space as reworking of LS moves sediment down hillslopes, into channels, and onto floodplains (Lang et al., 2003; Fuchs et al., 2011). LS may have a distinct lithology and geochemistry or it may be highly variable downvalley or between subwatersheds and indistinguishable from underlying sediment. Non-anthropic sediment will usually be mixed with anthropic sediment, so LS is usually diluted and rarely purely of anthropic origin. In regions with deep LS deposits the anthropogenic proportion is likely to be high. Several studies have shown greatly accelerated sediment deposition rates after disturbance and relatively slow background sedimentation rates (Gilbert, 1917; Knox, 2006). Although there are important exceptions to the assumptions of low pre-settlement and high post-settlement sedimentation rates in North America (James, 2011), pre-Columbia sediment accumulation rates were generally an order of magnitude lower than post-settlement rates. Thus, PSA is likely to contain a high proportion of anthropogenic sediment, and the assumption of substantial proportions of anthropic sediment in such a deposit is often appropriate.

2.4. Beyond North America

The definition of LS should extend to deposits generated over a wide range of geographic domains and from prehistory to recent time. For example, vast sedimentary deposits in Australia and New Zealand have been well documented as episodic responses to land-use changes following European settlement (Brooks and Brierley, 1997; Gomez et al., 2004; Brierley et al., 2005). These deposits are in many ways similar to those in North America and represent a legacy of relatively recent destructive land use superimposed on relatively stable pre-colonial land surfaces. Moreover, LS can also be used to describe Old World sedimentary units that were in response to episodic land-use changes. Sedimentation episodes have been documented in Eurasia for various periods of resource extraction or settlement (Lewin et al., 1977; Lang et al., 2003; Macklin and Lewin, 2008; Houben, 2008; Lewin, 2010). Older periods of episodic erosion and sedimentation associated with human settlement in Europe have been documented as far back as the Neolithic, Bronze Age, and Iron Age in parts of Europe and Britain (Macklin and Lewin, 2008; Dotterweich, 2008; Reiß et al., 2009; Dreibrodt et al., 2010). In some locations, multiple phases of LS generation can be inferred from Neolithic, Roman, or later gullies that once produced sediment but have subsequently been filled in with younger deposits (Dotterweich, 2005; Vanwalleghem et al., 2006; Reiß et al., 2009). In short, major sedimentary deposits produced episodically by logging, mining, domestic grazing, or agriculture in the Old or the New World can be referred to as LS.

2.5. LS as a stratigraphic unit

From a stratigraphic perspective, LS may be described by two types of materials: lithostratigraphic units (LSU) or chronostratigraphic units (CSU). A LSU is identified on the basis of distinctive lithic [or pedogenic] characteristics and conforms with the Law of Superposition; that is, it lies above older sediment and may be buried by younger sediment (NACSN, 2005). These are the units that are mapped in the field based on their physical properties (Murphy and Salvador, 1994). A CSU serves as the reference material for other sediment deposited during the same period of time. It should consist of materials of only a certain time period. Applying either classification to LS has strengths and weaknesses; problems not unique to LS. As a lithostratigraphic unit, LS generally conforms with Steno's Law of Superpositioning, but it may not have common lithologic or pedogenic characteristics between different catchments or regions that distinguish it from other sediment in that catchment. Yet, LS can often be identified on the basis of soil stratigraphy, sedimentary textures or structures, geochemistry, or fossils, and these features may be used to identify sources (fingerprinting) or to infer processes and environments of formation. As a chronostratigraphic unit, LS may be time transgressive and vary in age across the landscape as changes in land use often varied through time. Yet, LS often represents a distinct period of human land use and settlement that can be identified by relative dating or cultural artifacts and traced across a landscape. This can make LS an important tool for documenting Anthropocene history.

3. Implications of episodicity

Given the ubiquity of anthropogenically accelerated sediment production during the late historic period, it could be argued that all historic sediment has a component of anthropogenic inputs and should be defined as LS. Instead, LS should be reserved for deposits that represent substantially accelerated rates of sedimentation due to a component of anthropogenic disturbance. Thus, LS should not be used synonymously with 'historical' sediment *sensu stricto*, because LS carries the connotation of episodically produced anthropogenic sedimentation. This does not preclude sedimentation events generated, in part, by climatic change or tectonics as long as substantial production was generated by human activity.

During periods of intensive land use; e.g., clearance and plowing for agriculture, grazing, timbering, mining, etc., an episode of high sediment production may result in channel aggradation downstream. In extreme cases, aggradation may extend onto floodplains where large volumes of anthropogenic sediment may be stored (Fig. 3). When the intensive land-use practices cease and sediment production returns to background levels, channels usually incise, leaving large deposits on the former floodplain as terrace deposits. Following relatively rapid channel down-cutting, lateral erosion of channels takes a much longer time to widen floodplains and erode the stored LS (Simon and Hupp, 1986). Thus, the initial return of channels to their pre-disturbance base levels and gradients occurs long before the erosion and reworking of LS is complete. Such a sequence can be described as an *aggradation–degradation episode* (ADE) (James and Lecce, 2013) and represents the passage of a bed wave and a sediment wave (James, 2010). Protracted sediment production from this long term reworking represents a form of temporal connectivity in which the system memory of past sedimentation events is propagated into the future. If the floodplain had been relatively stable prior to the event, a distinct soil may have formed on it. In many cases, the LS deposits left behind by the ADE may be distinguished from the earlier alluvium by an abrupt contact of recent alluvium overlying a buried soil that can be seen in bank exposures and cores (Fig. 4).

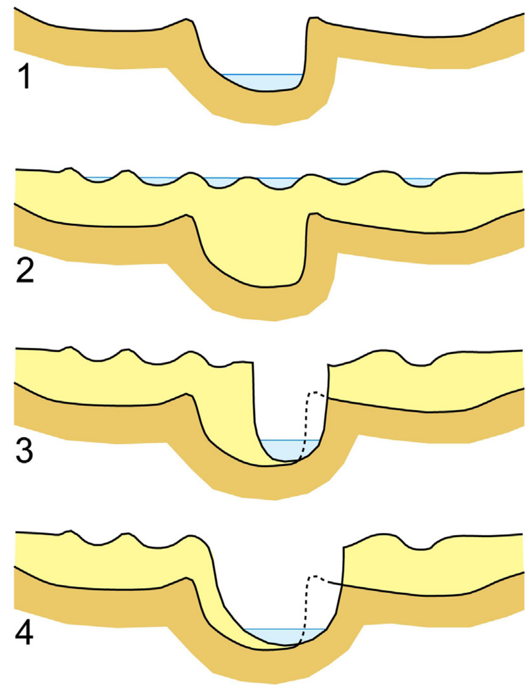

Fig. 3. Four phases of an aggradation–degradation episode (ADE): (1) single thread channel prior to disturbance; (2) channel and floodplain aggrade; possibly forming forming a braided channel, in response to sediment loads in excess of transport capacity; (3) as sediment loads return to background levels, channels rejoin and incise down to original levels; (4) channels widen over a longer period of time. See James and Lecce (2013) for description of ADEs.

The post-settlement period in North America provides many widespread examples of ADEs. Accelerated sediment production began with land clearance, hillslope erosion, and sediment deliveries in small catchments early in the sequence. Later, post-settlement alluvium arrived down-valley, channels aggraded, and floodplains were buried by overbank deposition. As land-use pressures decreased in the mid-twentieth century—possibly in response to cessation of farming or mining or to initiation of soil conservation measures, and possibly aided by dam construction upstream—sediment deliveries decreased, channels incised, and former aggraded floodplains were abandoned as terraces. In many places channel beds have returned to pre-settlement base levels and are slowly widening their floodplains. LS may continue to be reworked by this process and delivered to lower positions in large basins for many centuries. Recognition of these protracted responses to LS is essential to an understanding of watershed sediment dynamics.

4. Types and geomorphic positions of LS deposits

The production of LS comes from a variety of sources and deposits are located in a variety of geomorphic positions on the landscape. LS may occur on hillslopes as colluvium, as alluvium on floodplains and wetlands, or slack-water or deltaic deposits in lakes and estuaries (Table 2). Production of most LS begins on uplands and much of the sediment does not travel far, so colluvial deposits can be very important. This may not be widely recognized because deep and widespread colluvial deposits are largely unexposed and may not be mapped. Colluvial deposits of LS include midslope drapes, aprons, and fans. Drapes of relatively thin sheetflow deposits near erosion sites can be widespread, discontinuous, or may grade down to aprons or fans. Wedge-shaped aprons are deposited by sheet wash at the base of slopes

Fig. 4. Legacy sediment overlying pre-settlement soil in bank of Clarks Fork, tributary to Broad River, South Carolina Piedmont. Contact at tip of arrow. LS is ~1.5 m thick of stratified sand and silt with A/C profile at top. Lower pre-settlement alluvium has brown forest soil. Photographed November, 2012 by author.

where gradients decrease. Colluvial and alluvial fans form at the mouth of gullies and channels (Bierman et al., 1997).

Floodplains may store tremendous volumes of LS in forms that reflect the abundance of sediment relative to transport capacity. For example, the lower Yuba River in California contains an estimated 250×10^6 m^3 of hydraulic mining sediment from the 19th century (Gilbert, 1917). When relatively fine-grained deposits on floodplains overwhelm the transport capacity and the topography of the river, the deposits will be graded; i.e., they will form gradually sloping continuous beds (Mackin, 1948)

Table 2
Types of LS deposits.

Hillslopes – colluvial deposits from mass wasting, sheet flow, rills, or gullies.
*) **Midslope drape**: near site of erosion.
*) **Apron**: sediment wedge at base of slope.
*) **Fan**: at mouths of gullies, debris flows, and tributaries.

Floodplains – alluvium from lateral and vertical accretion.
*) **Graded**: excessive sediment buries floodplains down-valley in continuous deposits.
*) **Cascading**: abundant sediment arrayed in series of separated pockets.
*) **Punctuated**: limited sediment supply; LS only at local storage sites.

Lakes, wetlands, estuaries, and other low-lying areas – prograding deltas and fine-grained slackwater deposits.

Beaches – fluvial sediment delivered to coastal area beach-dune complexes.

Source and sink – local storage near production sites; no storage through steep, narrow transfer zone; large deposits at break in slope in lower valley.

Fig. 5. Legacy sediment on Greenhorn Creek, California composed of hydraulic gold mining tailings. High terrace is ~30 m above present channel. At the time of maximum sediment production, braided channels were graded at the high terrace level. When mining ceased, the channel incised, although it has not yet returned to pre-mining levels (James, 1989). Photographed December, 2004 by author.

(Fig. 5). These graded LS deposits do not depend on barriers for deposition and preservation to be effective. If LS is fairly abundant but geologic or engineering structures present substantial barriers to transport, intermittent sediment may collect in pockets resulting in a cascading series of frequent but separated deposits. For example, cascading LS deposits may occur in a series of wide, flat valley segments, or in a string of mill dams (Merritts et al., 2011). Punctuated LS floodplains occur with less sediment, greater transport capacity, or fewer topographic accommodation spaces, so that LS only collects in occasional isolated pockets, such as wetlands or impoundments. This is common in sediment starved areas such as glacially eroded landscapes in some parts of New England. Alluvium and slackwater LS deposits dominated by silts and clays may form in wetlands, lakes, estuaries, and other low-lying areas (Marcus et al., 1993; Hupp et al., 2009; Gellis et al., 2009). They also may grade to deltaic deposits in lakes, rivers, and coastal zones. Anthropic sediment delivered to coastal areas by fluvial systems has fed beaches and beach-dune complexes. These contributions often have gone unrecognized, however, for several reasons:

1) Identifiable characteristics of the fluvial sediment are stripped by winnowing of fines and abrasion of sand grains, so the evidence of their origin is obscured.
2) Modern dams and reservoirs now arrest much of this sediment before it reaches the coast.
3) Substantial sediment dilution occurs by longshore and other processes.

In spite of these difficulties, the potential historical contributions of LS to coastal sediment budgets should be recognized. Some evidence indicates that anthropogenic floodplain sedimentation rates may be higher within the tidal range of rivers (Woodruff et al., 2013).

At a geographically extensive scale, the spatial pattern of a LS deposit may be partitioned into *source and sink* zones with local storage of LS near the zone of production and one or more large zone of storage downstream where valleys are wide and gradients are low (Fig. 6). These zones may be separated by a zone of transport with little storage due to lack of accommodation space or high transport capacity. In the transport zone, channels enter steep, narrow valleys that efficiently convey sediment. The three-zone model of LS distribution often applies to historical lumbering or mining disturbances in mountainous

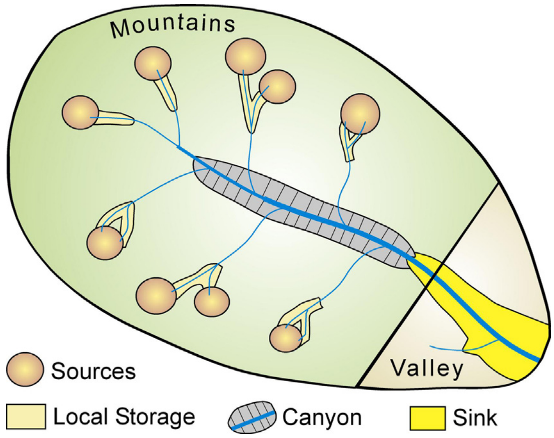

Fig. 6. Conceptual model of *source and sink* type of LS deposits. Some local storage occurs near sources in mountainous terrain but most storage is downstream where valley-bottoms broaden and gradients decrease. Sources and sinks are separated by relatively steep, narrow transport zone with negligible storage.
Adapted from James (2006).

areas and loosely fits Schumm's (1977) model of three zones of the fluvial system.

5. Processes governing LS deposition and preservation

The highly variable spatial distributions of LS often observed in North America call for explanation. Spatial heterogeneity reflects the highly irregular patterns of production, deposition, and preservation of anthropogenic sediment. A conceptualization of the processes influencing sediment deposition and storage can be instructive for understanding this variability.

5.1. Sediment production, delivery, and transport capacity

The production of sediment (erosion) on a hill slope (P_S) depends on landscape sensitivity, the intensity of land use, and external factors. Landscape sensitivity is governed by biogeomorphic factors, such as slope, lithology, soils, and vegetation. Land-use intensity depends on cultural and socioeconomic factors, such as population density, land-use technology, export economies, and conservation practices. Exogenetic factors include extreme meteorological events, climate change, or tectonics. The amount of sediment that is delivered to a site (D_S)—critical to understanding where LS may be deposited and how long it will be stored—is usually substantially different than the amount of sediment produced on hill slopes due to storage or recruitment of sediment in transit (Phillips, 2003). The proportion of sediment that is delivered is usually much less than 100% due to a dominance of deposition and storage over recruitment. This is especially true during episodic events when accelerated erosion results in a surplus of sediment production beyond equilibrium loadings.

Sediment delivery depends not only on sediment production on hill slopes, but also on conditions that govern deposition and recruitment, including transport capacity, sediment characteristics, and valley-bottom conditions. Many of these factors are scale-dependent and vary systematically with drainage area. Sediment characteristics that influence deliveries include grain size, shape, cementation, imbrication, and armoring. Relevant valley-bottom factors include morphology, floodplain width, position relative to channels, geologic structure, valley gradient, base-level, history of sea-level change, previous history of channel aggradation or incision, glacial history, and human alterations (channel-bed mining, dams, levees, etc.) (Belmont, 2011; Blum and Törnqvist, 2000; Nardi et al., 2006). Storage potential also depends on local connectivity between lateral and longitudinal linkages and blockages referred to collectively as (dis)connectivity (Fryirs, 2013). Blockages consist of buffers, barriers, and blankets that limit lateral, longitudinal, and vertical connectivity, respectively. This provides a means of identifying and tallying sites where storage may accrue and of quantifying sediment storage potential and delivery. Storage components can be classified as '*stores*;' i.e., relatively temporary storage components, or '*sinks*;' i.e., relatively persistent storage components (Fryirs, 2013). Much of the sediment within channels may be considered to be stores, whereas floodplains are largely sinks. Contrary to common perceptions, natural floodplains are generally not flat; they contain a variety of small landform features such as scroll bars, splays, abandoned channels, natural levees, etc. (Happ et al., 1940; Wolman and Leopold, 1957; Florsheim and Mount, 2002).

Sediment transport capacity (T_C) is the cumulative ability to convey sediment over time, which can be expressed by various hydraulic parameters such as stream power or energy of flows available to carry the sediment. The applied hydraulic forces are driven by the magnitude and frequency of flows, so they are scale-dependent and time-variant. Thus, T_C is variable in space downstream and laterally across the floodplain and is sensitive to climate and hydrologic changes to the basin. The flow regime may be influenced by human activities that alter runoff; i.e., land-use changes that introduce sediment may also increase flood magnitudes and T_C.

5.2. Storage potential and retention time

One way to conceptualize the potential for LS storage at a site is as a *storage potential ratio* of sediment delivery to sediment transport capacity over time:

$$S_P = f\left(\frac{D_S}{T_C}\right) \tag{1}$$

where S_P is storage potential. When sediment delivery is equal to transport capacity over time, then the reach is transporting the load available and the stream at that location can be considered to be graded (Mackin, 1948) (Fig. 7). Under graded conditions, the product of sediment discharge and caliber should be proportional to the water and sediment load of the stream (Lane, 1955). If deliveries exceed transfer capacity ($D_S/T_C > 1$), however, some storage is likely. If deliveries greatly exceed transport capacity through time ($D_S/T_C \gg 1$), abundant deposition and channel aggradation is likely, even without barriers or sinks (Fig. 7b). Thus, the likelihood of LS being stored at a site is a function of a variety of processes and conditions governing sediment production, transport, and deposition, flow hydraulics over time, valley bottom characteristics upstream and at the site, and sediment characteristics. These relationships explain why thick graded LS deposits are common in the Southern Piedmont of the USA where erosion of thick residual soils produced large volumes of sediment, but LS deposits are punctuated and less common in glaciated basins with thin soils. For application to longer time scales, D_S and T_C can be defined to include variability in exogenous variables such as climate or tectonics.

The sediment delivery ratio (SDR) is defined as the sediment yield at a point (Y_S) as a proportion of the sediment produced upstream by hill-slope erosion (Roehl, 1962; Vanoni, 1975; Renfro, 1975; Dickinson and Wall, 1977; Robinson, 1977):

$$\mathrm{SDR} = \frac{Y_S}{P_S} \tag{2}$$

Due to storage between hill-slope sources and floodplains down-valley, the SDR is usually less than one and decreases downvalley systematically with drainage area (Roehl, 1962; Novotny, 1980; Shen and Julien, 1993) (Fig. 8). The decrease in

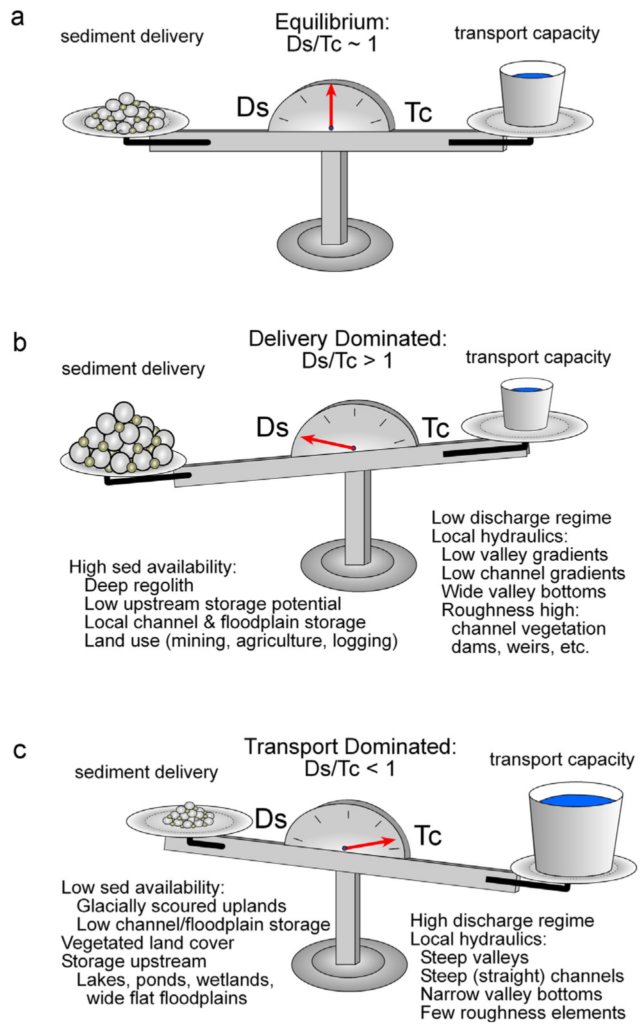

Fig. 7. Triple-beam balance metaphor for sediment storage potential: (A) sediment delivery (D_S) equals transport capacity (T_C) so channel is in equilibrium; i.e., no change in storage; (B) $D_S > T_C$ so net gain of sediment, aggradation, and high LS storage potential; (C) $D_S < T_C$ so net loss of sediment, degradation, and LS recruited from reach.
Concept adapted from Lane (1955).

SDRs downvalley was conceptualized as the 'sediment delivery problem' by Walling (1983) and recently restated by Fryirs (2013). An analysis of 16,571 annual observations for 87 Mediterranean badland catchments varying in size over 11 orders of magnitude indicates sediment yields are uniformly high (475 t ha^{-1} y^{-1}) for small catchments (<10 ha) but decrease two orders of magnitude from drainage areas ranging from 10^1 to 10^6 ha (Nadal-Romero et al., 2011). The preponderance of deposition in small watersheds suggests that LS deposits are most likely to be found in tributary locations if storage sites are available, but that this sediment will be reworked and redistributed downstream through time. A late 20th century trend in some North American catchments has been for SDRs that were much less than one, owing to high soil erosion rates, to increase as soil conservation measures were employed. As upland sediment production decreases, sediment yields remain constant by recruitment of LS from channel banks and floodplains (Robinson, 1977).

The dynamics implied by sediment delivery theory have great import to interpretations of LS. Sediment yields in the modern world are not static as was once assumed, but have a dynamic behavior that is largely driven by the legacy of past sedimentation events (Walling, 1996). Temporal variability occurs in the form of regional differences between large basins and by variability in sediment retention times within a basin. Regional differences reflect the cultural histories of landscapes; i.e., times of settlement and intensities of land use, as well as differences in the physical characteristics. Variations in sediment retention time within a catchment is one of the greatest sources of uncertainty in computing sediment yields and sediment budgets for watersheds (Wolman, 1977; Gellis et al., 2009). Temporal connectivity is an important element of LS and sediment delivery theory, because past deposits are reworked and transported downslope for long periods of time after initial deposition. This is, in fact, why 'legacy' is an appropriate way to describe these sediments; they are an inheritance from times past that should be reckoned with.

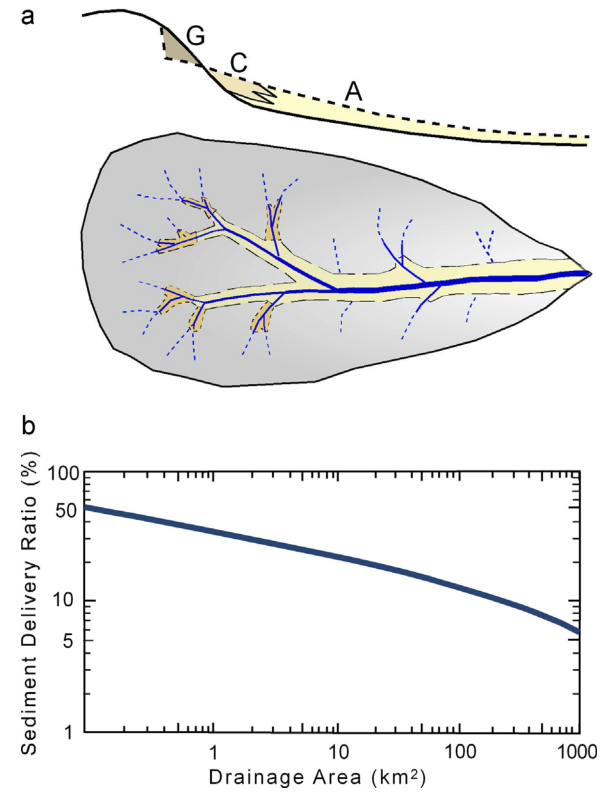

Fig. 8. Downstream changes in sediment deliveries due to storage in bed (A) result in rapidly decreasing sediment delivery ratios downstream (B). G: gully; C: colluvium; A: alluvium.

6. Conclusions

Numerous studies of anthropogeomorphic impacts since the Neolithic have documented sedimentation events in a variety of geomorphic environments. Legacy sediment (LS) is now commonly used in geomorphic, ecological, water quality, and toxicological studies to describe post-settlement alluvium on river floodplains. Most applications of LS imply or explicitly attribute the sediment to human landscape changes, but explicit definitions have been lacking that are sufficiently broad to apply LS to the variety of applications now common. The concept of LS should apply to anthropogenic sediment that was produced episodically over a period of decades or centuries, regardless of position on the landscape, geomorphic process of deposition, or sedimentary characteristics; i.e., it may occur as hillslope colluvium, floodplain alluvium, or lacustrine and estuarine slackwater deposits. LS can be defined with expanded geographic and temporal limits to include episodic human land-use activities wherever and during whatever period of pre-history or history in which they occurred.

Anthropogenic sedimentation has recurred globally throughout the Anthropocene in response to a variety of agricultural or resource extraction activities that accelerated sediment production. Mining, intensive agriculture, and logging generated recurrent episodes of LS production, associated with Roman outposts in Europe, and western colonization of North and South America, Australia, and other areas of Oceania. Recognition of these widespread and highly diverse legacies of human activities is important for a proper interpretation of watershed dynamics at a broad range of scales.

Legacy sediment is deposited when intensified land-use results in sediment deliveries greater than sediment transport capacity. This may lead to valley-bottom aggradation, which is ultimately followed by channel incision when the sediment wave passes and sediment loads decrease. This aggradation–degradation episode (ADE) tends to leave large volumes of LS in storage because vertical channel incision occurs much more quickly than channel widening. Many river systems in North America are still in the widening phase of adjustment to an ADE. Channel beds have returned to presettlement elevations but LS remains stored in extensive terrace deposits. The lagged responses and prolonged sediment recruitment represent a temporal connectivity. Recognition of these processes and the inherent imbalance in fluvial systems caused by tremendous volumes of LS storage is essential to wise policy development in river science, stream restoration, aquatic ecology, and flood risk management.

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