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RESEARCH ARTICLE

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Fire-produced coarse woody debris and its role in sediment storage on hillslopes

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Abstract

Interactions between vegetation and sediment in post-fire landscapes play a critical role in sediment connectivity. Prior research has focused on the effects of vegetation removal from hillslopes, but little attention has been paid to the effects of coarse woody debris (CWD) added to the forest floor following fires. We investigate the impacts of CWD on hillslope sediment storage in post-fire environments. First, we present a new conceptual model, identifying "active" storage scenarios where sediment is trapped upslope of fire-produced debris such as logs, and additional "passive" storage scenarios including the reduced effectiveness of tree-throw due to burnt roots and snapped stems. Second, we use tilt table experiments to test controls on sediment storage capacity. Physical modeling suggests storage varies nonlinearly with log orientation and hillslope gradient, and the maximum storage capacity of log barriers in systems with high sediment fluxes likely exceeds estimates that assume simple sediment pile geometries. Last, we calculate hillslope sediment storage capacity in a burned catchment in southwest Montana by combining high-resolution topographic data and digitization of over 5000 downed logs from aerial imagery. We estimate that from 3500–14 000 m^3 of sediment was potentially stored upslope of logs. These estimates assume that all downed logs store sediment, a process that is likely temporally dynamic as storage capacity evolves with CWD decay. Our results highlight the role that CWD plays in limiting rapid sediment movement in recently burned systems. Using a range of potential soil production rates (50–100 mm/ky), CWD would buffer the downslope transport of ~35–280 years of soil produced across the landscape, indicating that fire-produced CWD may serve as an important source of sediment disconnectivity in catchments. These results suggest that disturbance events have previously unaccounted-for mechanisms of increasing hillslope sediment storage that should be incorporated into models of sediment connectivity.

KEYWORDS
coarse woody debris, erosion, fire, hillslope sediment transport

1 | INTRODUCTION

Coarse woody debris (CWD), which describes a variety of materials including standing dead trees (snags) and downed logs, branches, and stumps where the minimum diameter generally ranges from 2.5 to 15 cm, influences hillslope and stream processes in forest environments. CWD plays an important role in carbon and nutrient cycling (Harmon et al., 1986), promotes the germination and growth of various plants and fungi, and provides feeding, reproduction, and sheltering sites for animals (Harmon et al., 1986; Lindenmayer et al., 2002; Lohr et al., 2002; Sass, 2009; Svensson et al., 2016). CWD also plays an important geomorphic role, which has primarily been documented in fluvial environments (Bendix & Cowell, 2010; Magilligan et al., 2008; Nakamura & Swanson, 1993; Polvi & Wohl, 2013;

Welling et al., 2021). Within forested mountain streams, CWD (also termed instream wood or large woody debris) promotes sediment storage by acting as physical impediments to sediment transport (Andreoli et al., 2007; Marston, 1982; Wohl et al., 1997) and it increases hydraulic roughness, thus decreasing flow velocity and further promoting sediment deposition (Abbe & Montgomery, 1996; Davidson & Eaton, 2013; Manga & Kirchner, 2000; Wilcox & Wohl, 2006).

The importance of live vegetation in hillslope sediment storage and transport is widely recognized, yet the impact of CWD (dead vegetation delivered to the surface) on hillslope geomorphic processes has received little attention (Amundson et al., 2015; Marston, 2010; Rengers et al., 2016; Schmidt et al., 2001). The uprooting and subsequent toppling of trees in forests—the process of tree-throw—transports soil downslope and alters hillslope form by creating pit-and-mound topography (Gabet & Mudd, 2010; Gabet et al., 2003). Live vegetation can also act as a dam that buffers downslope sediment movement (e.g., Dibiase & Lamb, 2013; Lamb et al., 2011, 2013) where sediment storage volumes vary with plant width, hillslope angle, and sediment size. Furthermore, the removal of live vegetation following a disturbance such as wildfire has been widely recognized to induce changes to sediment routing through watersheds, including increased erosion rates and destabilized slopes (Dethier et al., 2016; Dibiase & Lamb, 2013; Greenway, 1987; Swanson, 1981).

Though disturbances to vegetation such as the uprooting of trees contribute to erosion and sediment transport on hillslopes, they also add CWD to the ground surface and may provide a damming effect similar to live vegetation (Smith & Swanson, 1987). In addition to tree-throw, CWD is supplied to forested landscapes by a variety of other mechanisms such as wind, insects, disease, suppression, mass movements, and fire (Harmon et al., 1986; Silvério et al., 2019). These mechanisms can produce hillslope-wide disturbances and amass large volumes of CWD in a single event (Spies & Cline, 1988) as opposed to the process of tree-throw, which typically affects a single tree. The potential for CWD to increase sediment storage on hillslopes is underscored by previous assessments of soil stabilization treatments using constructed log barriers. The manual installation of contour-felled logs on hillslopes, to act as dams limiting downslope sediment movement, is commonly implemented following fires to mitigate post-fire erosion (e.g., Robichaud, Pierson, et al., 2008; Robichaud, Wagenbrenner, et al., 2008). Sediment storage by contour-felled logs likely depends on factors including slope, vegetation regrowth, and rainfall intensity (and storage is greatest in the first few (1–3) years following fires) (Badía et al., 2015; Myronidis et al., 2010; Robichaud, Pierson, et al., 2008; Robichaud et al., 2009).

Few studies have noted the role of naturally emplaced (in contrast to installed) logs as debris dams (Harmon et al., 1986; Raska, 2012; Wilford, 1982). Smith and Swanson (1987) highlighted the potential importance of CWD as sediment barriers following the Mount St Helens eruption, finding that storage upslope of logs accounted for a third of the total volume of tephra stored on hillslopes. The task of investigating the role of CWD on hillslope evolution and response to disturbance events is becoming increasingly important as the size and intensity of wildfires are projected to increase over the next century, particularly in the western USA (Littell et al., 2009; Westerling et al., 2006).

Knowledge about the individual components affecting sediment storage and transport by CWD on hillslopes needs to be complemented by synthesis and application to the explicit study of the effects of CWD on hillslope sediment storage. Therefore, the main objective of this paper is to provide a foundation for studying the geomorphic role of CWD on hillslopes in fire-affected landscapes. We address this objective via three study elements. First, we combine field observations from recently burned landscapes in southwestern Montana and existing knowledge to develop a conceptual model detailing scenarios in which CWD affects sediment storage and transport on hillslopes, focusing on post-fire environments. Second, we extend our conceptual model by investigating the effects of logs on sediment storage through a remote survey. Third, we present results from a small-scale physical model to test major assumptions on relationships governing the sediment storage potential of logs.

2 | GENERATING A HOLISTIC CONCEPTUAL MODEL FOR CWD STORAGE ON HILLSLOPES

2.1 | Guiding observations in post-fire landscapes

In 2018 and 2019 we visited two recently burned locations within the Bitterroot and Sapphire Mountains in southwestern Montana. Roaring Lion, a tributary in the Bitterroot Mountains draining to the Bitterroot River, experienced a ~ 36 km^2 fire in 2016 while a ~16 km^2 area in Rye Creek in the Sapphire Mountains burned in 1998. We surveyed the abundance, character, and impacts of CWD generated following fires in both systems. Regardless of time since fire, we observed abundant CWD on hillslopes, consisting mainly of snags and large downed logs.

Fallen logs had notable sediment storage upslope, especially those oriented near-parallel to the slope contours and perpendicular to the downslope direction (~90° log orientations). Multiple incidences of the domino effect whereby one tree or branch topples and strikes other healthy, damaged, or dead neighboring trees, causing further stem breakage or toppling (van der Meer & Bongers, 1996) were found, typically involving two to three downed trees, though also one impacting six trees. Log jams were common, especially near the base of slopes, and in large jams some logs were not in contact with the ground. In most cases, jams consistently stored both sediment and fine woody debris. Charred stumps were abundant within both systems, as was apparently fire-influenced tree-fall. In nearly all cases, snags broke along the trunk of the tree. In rare cases where complete trees were uprooted, roots appeared to have been plucked out of the ground, leaving deep, narrow holes rather than driving soil upturn and tree-throw. Burnt root fragments were also documented in pits, suggesting that fire damage caused the roots to snap. Though we cannot be certain that all stumps and CWD observed in the study area resulted from fire damage in the same event, the lack of other recent fire activity, combined with the frequency and density of charred stumps, strongly suggests that the majority of this debris was directly or indirectly produced as a result of the most recent fires. The combination of these observations led to the generation of our conceptual model outlined below.

2.2 | Conceptual model for hillslope sediment storage by CWD

We classify CWD–sediment interactions as either passive or active storage, described below, and outline examples of each (Figure 1).

2.2.1 | Passive storage

We use the term "passive storage" to describe scenarios where sediment transport processes, specifically tree-throw, are obstructed due to either the breakage of a tree stem or uprooting of a tree without upturning sediment (Figure 1). The prevention or obstruction of tree-throw does not prevent the initial transport of sediment, but it prolongs or passively stores sediment on hillslopes. Both "active" and "passive" storage occurs along the continuum of sediment transport on hillslopes between initial soil production and eventual erosion into streams. "Passive" storage increases the timescale of sediment storage on hillslopes by retaining sediment that would otherwise have been transported downslope via tree-throw. Because passive storage refers to the absence of tree uprooting, remaining broken stumps could serve as sites of storage for sediment cascading from upslope. In fire-affected systems, passive storage can occur through many mechanisms. Fire damage to tree stems can directly cause tree mortality through cambium necrosis or indirectly as a result of increased sensitivity to wind damage and infestations (Harmon et al., 1986; Hood et al., 2018). Burnt trees are typically weakened at or below breast height (Ryan et al., 1988) and may be more susceptible to breakage than uprooting (Veblen et al., 2001). Breakage converts a dead or damaged tree to a stump, considered to be any dead, standing tree less than ~1.4 m in height (Waskiewicz et al., 2015).

With respect to the domino effect, the probability of an impacted tree snapping a stem versus uprooting is dependent on multiple factors, including wood density and strength, degree of prior damage, tree height, and tree diameter at breast height (Putz et al., 1983). Although the minimum height for a tree to be susceptible to tree-throw is unknown, it is reasonable to assume that stumps are much less likely to uproot compared to taller trees. As a result, the creation of stumps either through breakage at a weakened point and/or impact via the domino effect reduces the possibility of tree-throw in post-fire landscapes and passively stores sediment on hillslopes.

Similarly, tree-throw processes may be partially obstructed when the roots of a tree are burned and subsequently weakened, resulting in root breakage instead of complete upheaval of the root plate. Roots can be damaged during fires as a result of long-term smoldering combustion, though transfer of heat to roots is less understood compared to the stem or crown (Hood et al., 2018). While this phenomenon has not been extensively studied, intense fires can result in burned roots well below the ground surface, in some cases burning the roots entirely and leaving a series of holes where they once had been (Hoffman & Anderson, 2014). Such severe damage to roots prevents the transport of soil by tree death and tree-throw. Similar processes likely occur in less severe fires, where burned roots snap or pull out during tree-fall, thus decreasing root plate volume of an uprooted tree. The reduced effectiveness of tree-throw sediment storage as a result of fire damage is likely dependent on factors including tree age, size, and species as well as soil moisture and fire severity.

2.2.2 | Active storage

We use the term "active storage" to describe scenarios where new fire-produced CWD acts as a direct barrier to soil and debris moving downslope. These logs act to buffer or inhibit sediment transport pathways and thus sediment accumulates upslope (Figure 1). CWD naturally delivered to the hillslope surface in post-fire systems may be randomly distributed, and the effectiveness of logs to act as sediment barriers would depend on the log orientation (whether it is parallel or perpendicular to contours), diameter, and length of snapped stems. In some cases, multiple logs may fall or migrate to the same location to form a log jam. Log jams provide storage at their upslope extent as well as pockets of deposition within the jam itself. The efficacy of log

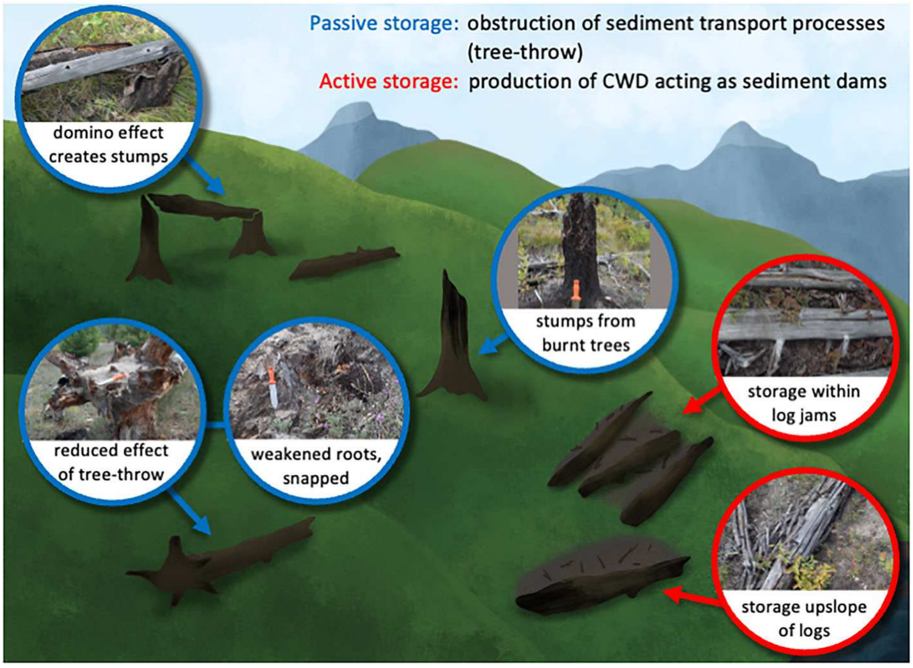

FIGURE 1 Conceptual model for the influence of fire-produced coarse woody debris (CWD) on hillslope sediment storage. "Active" storage scenarios (red circles) occur when sediment accumulates upslope of logs and within log jams, disrupting the downslope movement of sediment. "Passive" storage (blue circles) occurs through the suppression of geomorphic processes that would typically contribute to sediment transport processes. In this scenario, fire damage to tree roots and trunks results in snapping of weakened points, limiting or preventing the possibility of tree-throw, and effectively storing sediment on the hillslope that could have otherwise been mobilized by tree death and fall. The domino effect, where one falling tree causes toppling of neighboring trees, may enhance both passive and active storage. [Color figure can be viewed at wileyonlinelibrary.com]

jams to store sediment is likely influenced by the number of logs, slope position, size and age of individual logs, and the degree of contact that logs have with the ground surface—factors that have been documented to affect storage behind log jams within rivers (e.g., Wohl & Scott, 2017, and citations therein).

CWD production in post-fire environments may be enhanced in densely populated stands through the domino effect. Though not previously explicitly studied in post-fire systems, the domino effect can significantly add to mortality in other disturbance-driven systems. For example, in two studies, over 15% of the mortality of Douglas fir stands in a Pacific Northwest forest and nearly three quarters of fallen trees in a tropical rainforest in French Guiana were attributed to falling snags killing or damaging other trees (Franklin et al., 1987; van der Meer & Bongers, 1996). While the domino effect may add CWD to the forest floor, it may also result in the uprooting of trees and increased incidence of tree-throw if tree stems or roots are not weakened (as they are in passive storage scenarios). A study in an undisturbed forest of the Central Amazon highlights the dual role of the domino effect, whereby falling trees and snags broke adjacent tree stems, resulting in both 22% of observable stumps and 38% of tree-throw (Rankin-de-Merona et al., 1990).

Depending on species, climate, and other disturbances (i.e., subsequent fires), logs can persist in a landscape for >100 years (Harmon et al., 1986). The storage capacity of CWD likely varies with time, as it progresses through stages of decay. For example, initially a felled log might have its greatest thickness and density, but least amount of ground contact. This contact likely increases during decay and as sediment accumulates, further increasing capacity to store sediment. However, at advanced stages of decay log thickness may decrease along with the effective dam height. Thus, logs act as both temporary and time-variant agents of sediment storage at their upslope extent (Harmon et al., 1986).

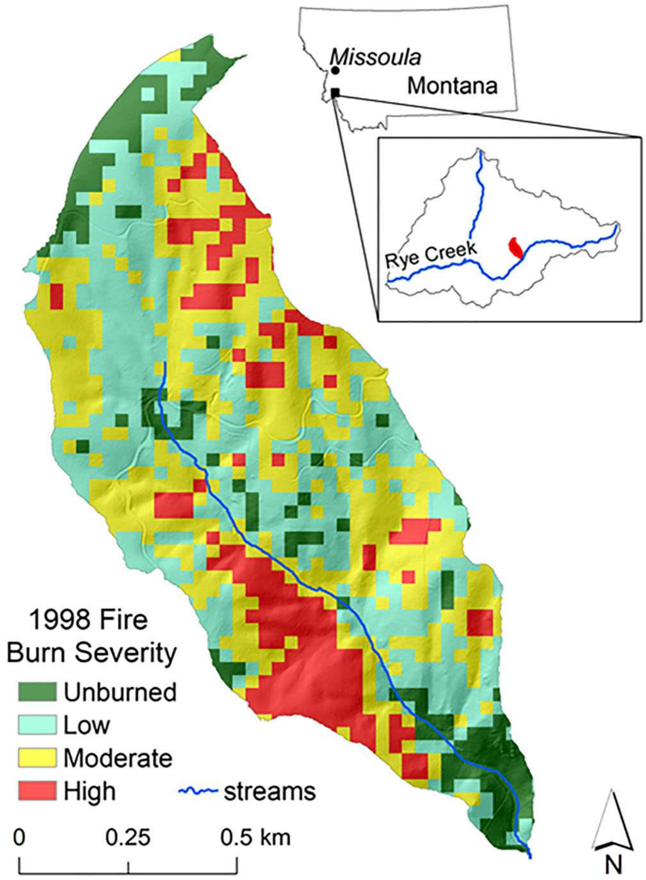

FIGURE 2 Our 1 km^2 study area is located in the Rye Creek catchment in western Montana. Over 85% of this area was burned in a mixed-severity fire in 1998 (burn severity data were obtained from the Monitoring Trends in Burn Severity (MTBS) project; Eidenshink et al., 2007). [Color figure can be viewed at wileyonlinelibrary.com]

3 | METHODS FOR MEASURING ACTIVE STORAGE SCENARIOS

3.1 | Study site

Our remote survey focuses on a small (1 km^2), first-order sub-catchment of Rye Creek in the southern portion of the Sapphire Mountains of southwestern Montana (Figure 2). This system is an ideal setting to study the interactions between coarse woody debris, sediment transport, and wildfire, due to its known fire history, the availability of LiDAR data, and prior work quantifying soil cover and weathering (Benjaram et al., 2022). The study site lies within a mixed conifer forest with primary species of Douglas fir, ponderosa pine, and lodgepole pine (Krist, 2010). A single defined channel drains the sub-catchment to Rye Creek, and surrounding hillslopes are predominantly soil-mantled (Benjaram et al., 2022), convex, and with gentle to moderate slopes averaging $\sim 18^\circ \pm 7^\circ$ ($\mu \pm$ SD based on 1 m resolution LiDAR data).

The study region has a semiarid climate (average precipitation and temperature average ~55 cm and 4.5° C, respectively; PRISM Climate Group, 2014) and is defined by a group III fire regime, which equates to stand-replacing fires with mixed-severity fires interspersed. The average fire return intervals in this region are 100–220 years for mixed- and stand-replacement severity fires, respectively, and 69 years for fires of all types (LANDFIRE, 2008). This system was almost entirely burned in the Bitterroot Complex fire in 1998 (Figure 2). During this event, 15% of the catchment burned at high severity, 37% at moderate severity, and 36% at low severity (Monitoring Trends in Burn Severity Project; Eidenshink et al., 2007). The large 2000 Valley Complex Fires burned much of the surrounding area but did not affect our site. No other fires have been recorded in this catchment since 1984.

3.2 | Remote survey methods

The goal of the remote survey was to quantify the volume of sediment that logs produced from the 1998 fire could store, as well as to evaluate the controls on sediment storage volume. Forty-seven aerial photographs, collected by the National Center for Airborne Laser Mapping (NCALM) in 2016, were processed in Agisoft Photoscan to generate a 9.4 cm resolution orthophoto that was then georeferenced in ArcGIS. Due to the size of the study area, a subset of data was selected by generating 55 random, 40 m radius areas of interest (AOIs) across our catchment.

Logs located completely or partially within each AOI were digitized as line features (Figure 3) in ArcGIS. Logs were identified visually

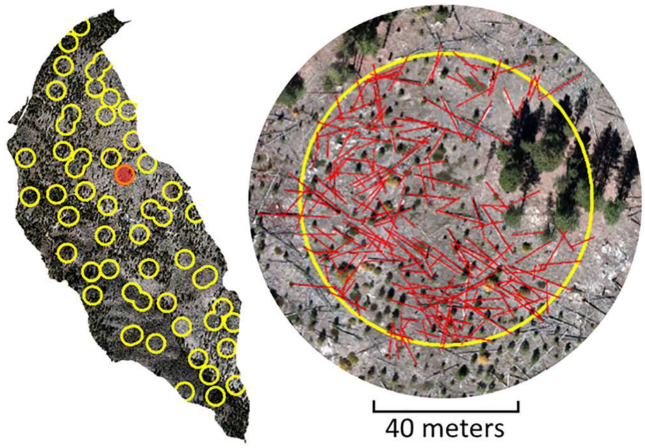

FIGURE 3 Areas of interest sampled throughout the catchment (yellow circles, left). Example of one area of interest highlighted in red on catchment map (left). Logs within and intersecting the area of interest are digitized as red line features (right). [Color figure can be viewed at wileyonlinelibrary.com]

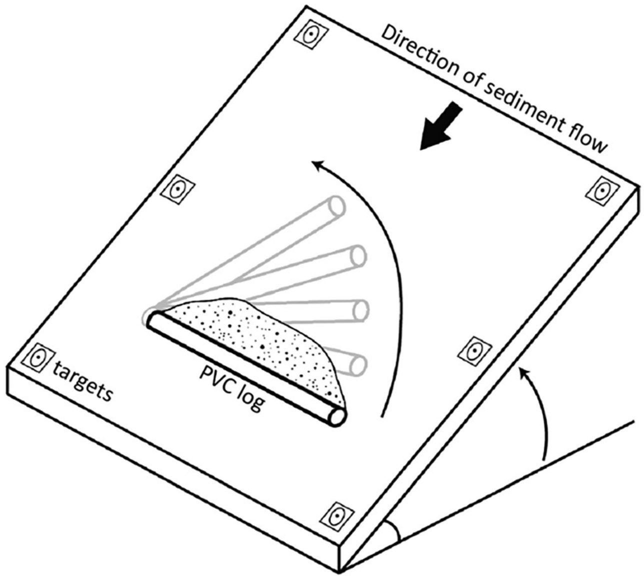

FIGURE 4 An adjustable tilt table was used to physically model sediment piles behind model (PVC) logs. Sediment was added at the top of the table until a steady-state condition where sediment pile geometry was unchanging. 2 mm DoDs were created in Agisoft PhotoScan using 15 before-and-after photographs in triplicate experiments at three slope angles and six model-log orientations.

and selected only if they had a consistent width of three or more pixels (approximately 28 cm in width) to reduce misidentification of coarse woody debris. This cutoff provides a conservative amount of CWD on hillslopes given that the accepted breakpoint between fine and coarse woody debris is 10 cm in diameter at a piece's thickest end (following standards from the Long Term Ecological Research network; Harmon & Sexton, 1996).

Topographic variables were generated in ArcGIS from a LiDAR-derived, 1 m resolution bare-earth digital elevation model (DEM), from which logs were excluded. Each digitized log was assigned an elevation, aspect, slope, curvature, and associated flow direction value calculated as the average of values of the bare surface over which the log crossed. Burn severity data were obtained through the Monitoring Trends in Burn Severity database (MTBS). Logs were assigned a burn severity value ranging from 1 (*unburned*) to 4 (*high severity*) following the same methodology as the topographic variables.

Potential sediment storage for each log was calculated according to Equation (3), using log lengths measured from aerial imagery and hillslope angles (θ) derived from 1 m DEMs. We assume log diameters of 0.25 and 0.5 m as these diameters represent a compromise between the minimum that we could confidently detect using aerial imagery and high-resolution topographic data and a conservative average of those observed in the field. Sediment storage calculations for the field study were only performed on logs oriented ≥45° from the flow direction and located on slopes ≥15° due to negligible accumulation occurring below either of these thresholds (following Measeles, 1994, and Smith & Swanson, 1987). Correlations between calculated sediment storage and potential explanatory variables such as slope and aspect were assessed by comparing the log orientation (a proxy for sediment storage) against each topographic variable.

3.3 | Physical model setup

To test assumptions used in our remote-survey quantification of "active" sediment storage upslope of logs, as well as to gain more insight into active storage scenarios, we physically model sediment storage in tilt table experiments. Similar experiments have been conducted to assess sediment storage in supply-limited landscapes (Lamb et al., 2013). Because those experiments focused on storage by live vegetation (yucca), storage capacity is limited by the width of the debris dam, whereas in our "active" storage scenarios storage is limited by the height and orientation of the dam. While insights provided by Lamb et al. (2013) are valuable, they are not easily transferable to the scenarios we consider here. The goal of these physical modeling experiments is to observe the geometry of sediment piles upslope of model "logs" and quantify the maximum storage volumes under different slope angles and log orientations. As such, we do not incorporate other variables that would affect sediment storage in a natural environment (i.e., grain size, cohesion, moisture, surface friction, etc.).

The experimental setup (Figure 4) consisted of a 0.61 × 0.61 m adjustable wood table and a 0.51 m long, 0.051 m diameter PVC pipe used to represent the log. The table was adjustable to slope angles of up to ~65° by changing the underlying table support rods. Model-log orientations were adjusted in 15° increments between 15° (relative to flow direction) and 90° (perpendicular to flow direction) by affixing the model log to the board using small lengths of dowel set into drilled holes. Holes that were unoccupied in each experiment were plugged to ensure no sediment loss.

We conducted 18 experiments at six model log orientations (15–90° in 15° intervals) and three table angles (30°, 45°, and 60°) in triplicate. In each experiment, coarse sand was steadily added to the top of the sloping board until maximum storage was attained. We visually estimated maximum storage occurrence when the sediment pile size and geometry remained constant.

Fifteen photos were taken using a Ricoh GR II compact DSLR camera at the start and end of each experiment. We referenced photos in Agisoft Photoscan using black and white targets placed in the experimental setup. DEMs were exported from Agisoft Photoscan at a 2 mm resolution. This resolution was the result of rounding up to the nearest integer from the suggested resolution from the software (<2 and >1 mm). Using ArcGIS, bare table DEMs were subtracted from

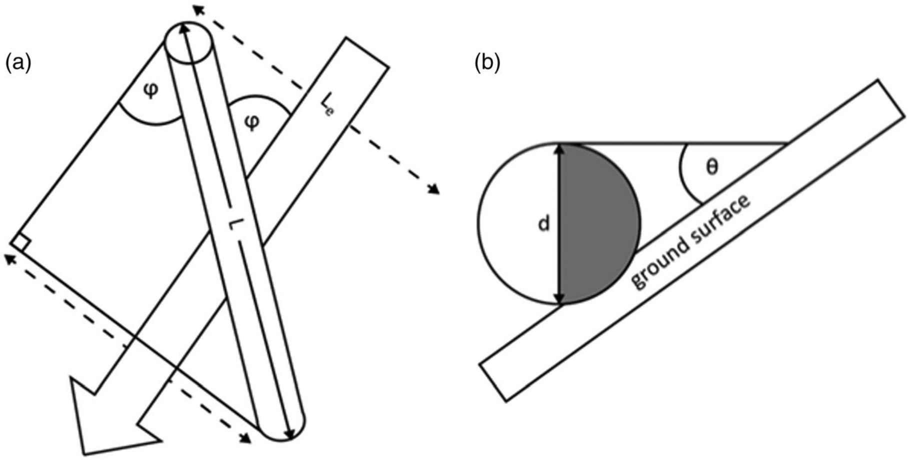

FIGURE 5 (a) Top-down view of a log on a hillslope surface. A log's effective length (L_e) as a barrier to sediment transport is dependent on its total length (L) and orientation (φ), which is the difference between the direction of steepest descent (hollow arrow) and the log axis. (b) Cross-sectional view of a log and upslope sediment wedge, following Equation (3).

DEMs of each experimental run to generate DEMs of difference (DoDs). We then calculated volumes from DoDs where the elevation difference exceeded 2 mm. Though this cutoff has the potential to underestimate sediment pile volumes, visible sediment pile extents based on pictures agreed well with regions above the 2 mm cutoff value; thus we provide a conservative geometry of sediment piles.

To determine expected maximum sediment storage in the model system, we used equations based on calculations for the potential storage of contour-felled logs (Myronidis et al., 2010). Naturally fallen logs should be found in a variety of orientations, influencing potential sediment storage (Figure 5), since logs aligned parallel to hillslope contours and perpendicular to flow direction result in the most effective storage. To account for the influence of log orientation, we calculate the effective log length (L_e) as

$$L_e = \sin\varphi \times L, \tag{1}$$

where log orientation (φ) is calculated as the smallest difference between the log axis and flow direction, and L is the log length. Potential sediment storage above a simple vertical dam (S_V) can be calculated as

$$S_V = \frac{d^2 L_e}{2\tan\theta}, \tag{2}$$

where d is the dam height and θ is the hillslope angle in degrees. Accounting for the cylindrical shape of log dams, the potential sediment storage above a cylindrical log dam (S_L) is

$$S_L = \frac{dL_e}{2}\left(\frac{d}{\tan\theta} - \frac{\pi d}{4}\right). \tag{3}$$

where d is the log diameter and θ is the slope angle in degrees. In this scenario, sediment storage is limited by the log length, diameter, orientation, and local hillslope gradient (Figure 6).

4 | RESULTS

4.1 | Remote survey results

We digitized 5328 logs within the 55 AOIs of the Rye study area. Of these, 2799 logs (~53% of the total) were oriented between 45° and 90°, where 90° is perpendicular to flow direction. Logs were found at all slope positions, with log abundance largely reflecting slope distribution (Figure 7) except for high slope angles (>40°) that make up a small part of the system (<5% of total area). Thirty-five percent of the digitized logs (1854) were on slopes above 15°, representing the final population of logs on which we base our sediment storage measurements.

The potential storage capacity of these logs, according to Equation (3) and assuming diameters of 0.25 and 0.50 m, averaged ~0.50 and 1.98 m^3, respectively. These calculated volumes expand to a total potential sediment storage capacity between ~920 and 3700 m^3 for the digitized region of our study area alone. If we assume that the AOIs (~26% of total area) together are representative of the study catchment, logs have the potential to trap between ~3500 and 14 000 m^3 of sediment over our 1 km^2 first-order watershed. Finally, we found no significant correlations between log density and topographic variables or burn severity (Figure 8). Pearson's correlation coefficients range from 0.04 to 0.09 for explanatory variables.

4.2 | Physical modeling results

The volumes of sediment piles observed in physical modeling experiments were observably different from volumes based on Equation (3) (Figure 9), with the exception of our steepest hillslope angle scenario (60°), where the volumes were comparable. First, we found little sediment accumulated upslope of logs oriented <30° from flow direction. At more contour-parallel orientations, however, observed volumes greatly exceeded estimated volumes.

In addition, sediment piles in each model experiment had complex morphologies that changed with table tilt angles (Figure 10). Equations (2) and (3) follow the approach of Myronidis et al. (2010) in assuming a relatively simple geometry where a triangular wedge of sediment with a flat surface forms upslope of a log. Modeled sediment piles extended higher than these surfaces (Figure 10). We might intuitively expect pile volumes to exceed those predicted by Equation (3), considering granular solids such as soils and sediments should heap to an angle of repose dependent on inherent characteristics such as particle size, roughness, and cohesion (Al-Hashemi & Al-Amoudi, 2018). The steepness of the pile surfaces changed, however, as they extended from the top of the log barrier to where they met the upper table surface (Figure 10a, expected versus observed). The profiles generated assuming Equation (3) have no such inflexion point.

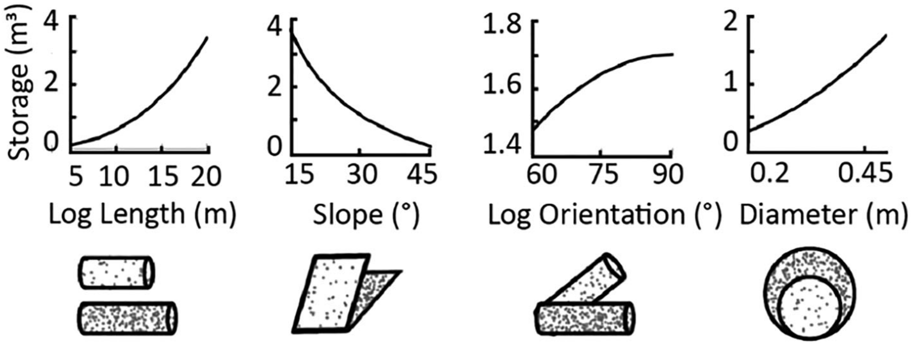

FIGURE 6 Effects of log length, orientation, and diameter, as well as hillslope angle, on sediment storage capacity, as defined by Equation (3). Intuitively, logs that are longer, larger in diameter, and are situated perpendicular to the dominant flow direction have a larger sediment storage capacity. Logs on gentler slopes will also have a greater sediment storage capacity than logs on steep slopes.

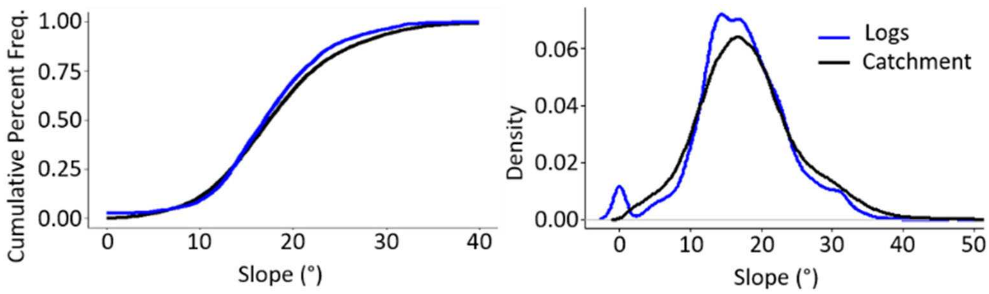

FIGURE 7 Frequency and density distributions of slope for the entire study area (black lines) and areas underlying logs (blue lines). Results from Kruskal–Wallis test (H[3.5], $p = 0.06$) indicate that there was no statistically significant difference between log slopes and catchment slope (considering catchments slope ≤ 40°). [Color figure can be viewed at wileyonlinelibrary.com]

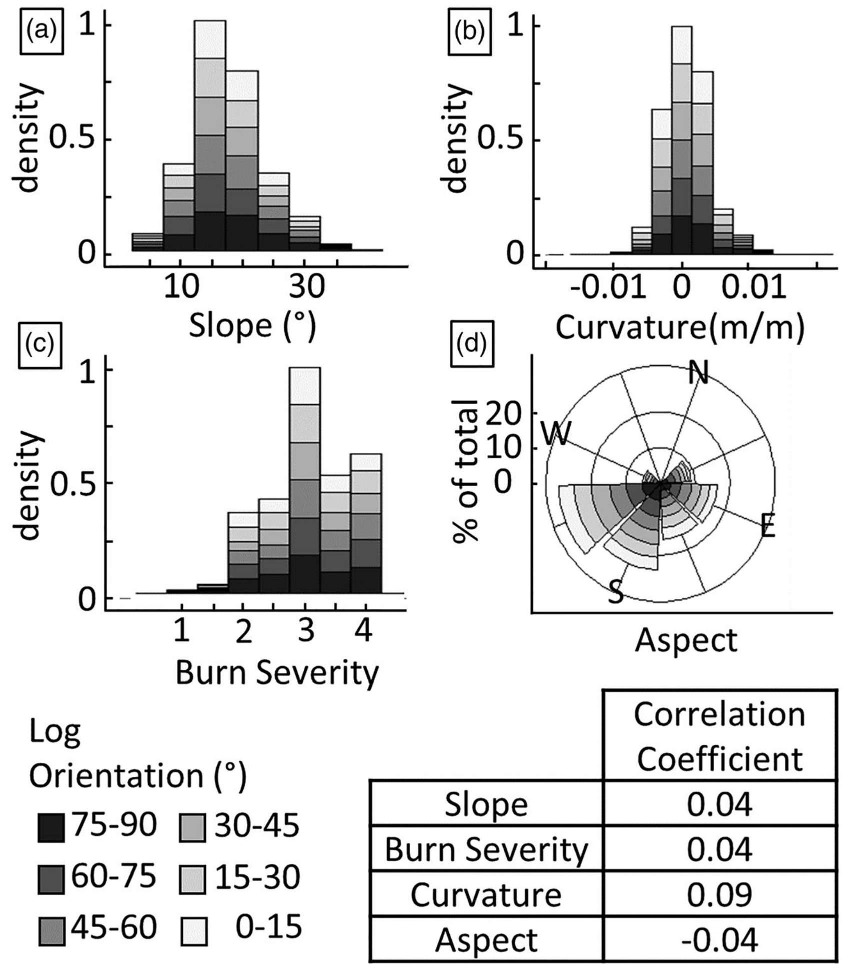

FIGURE 8 Relationships between density of all digitized logs, subdivided by log orientation, topography (a,b,d), and burn severity (c). Broadly, log orientations have similar distributions regardless of topography or burn severity, as supported by the low Pearson's correlation coefficients shown here.

Furthermore, the surface slope of sediment piles (both above and below the inflexion point) increased as the table angles increased.

These results illustrate the challenge of developing a generalized set of adapted equations to describe sediment piles above logs. However, in these experiments, sediment piles are formed by a constant and unlimited sediment supply from above, such that the observed storage is limited by orientation and table slope, and not by sediment flux. This scenario is unlikely to apply in the case of short-

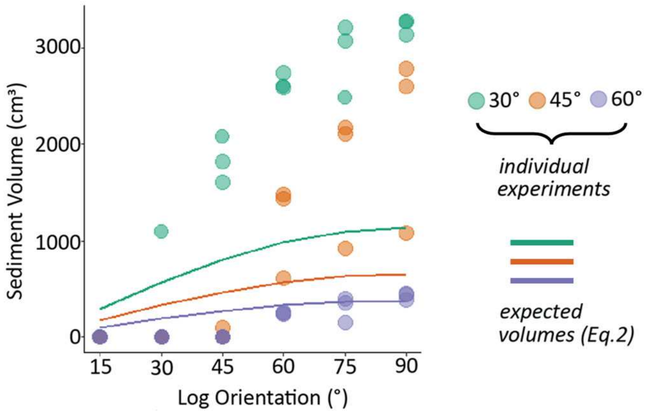

FIGURE 9 Observed versus expected sediment pile volumes calculated using Equation (3). No storage occurred during model runs with logs oriented <15° from the direction of steepest descent, regardless of table angle. Observed sediment volumes tend to be noticeably higher than expected for the 30° and 45° slope experiments. The 60° slope experiments show rough agreement between observed and expected sediment storage volumes. [Color figure can be viewed at wileyonlinelibrary.com]

term storage by logs on hillslopes, especially on low-gradient slopes. Thus, while predictions by Equation (3) represent underestimates of maximum pile volumes, they may reflect reasonable—though conservative—estimates of potential storage in natural systems with limited and/or intermittent sediment flux.

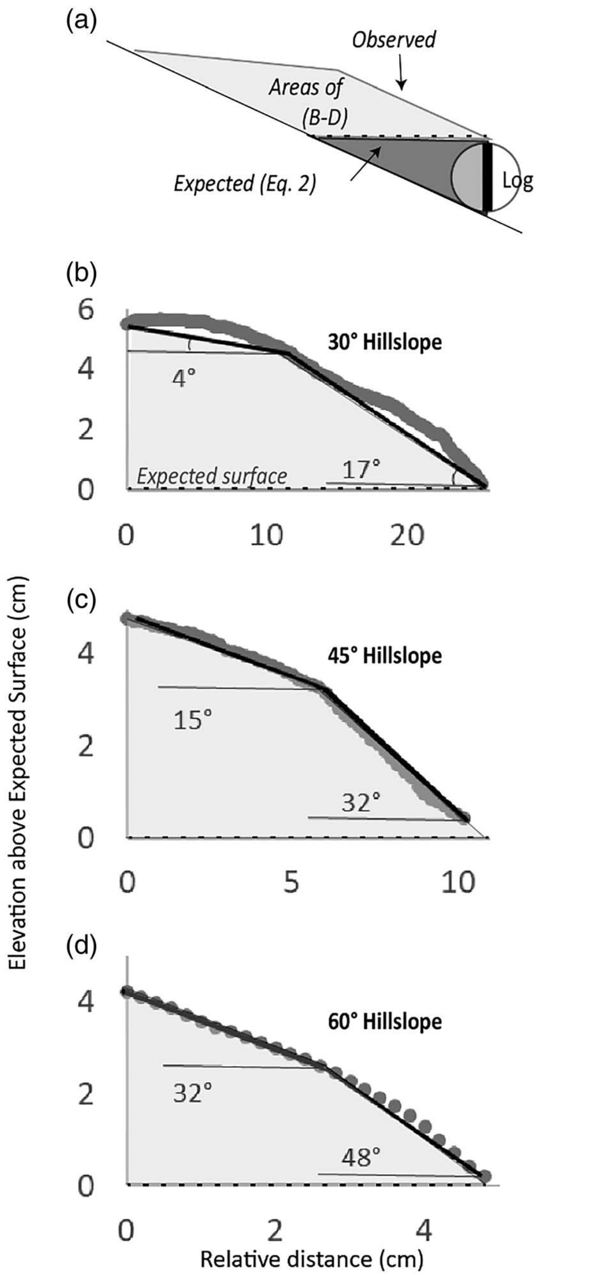

FIGURE 10 (a) Prior work on contour-felled logs and Equations (2) and (3) predict simple sediment pile geometries (dark grey region) that extend horizontally from the top of a log barrier to the hillslope surface. By contrast, physical model experiments resulted in larger sediment piles with more complex geometries (expanded by the light-grey region). (b–d) Sediment pile cross-sections taken from slope-normal (90° orientation) logs at three table angles. Vertical and horizontal axes vary between panels. Grey dots are elevations determined from high-resolution DEMs, and black lines reflect generalized surfaces and highlight breaks in slope. Gradients of pile surfaces both above and below the break in slope increase with increasing table angle.

5 | DISCUSSION

Interactions between fire, CWD, and sediment storage and transport on hillslopes have been previously recognized (Badia et al., 2015; Myronidis et al., 2010; Raska, 2012), but have yet to be evaluated in the context of landscape evolution or sediment connectivity. We present a conceptual model that, to our knowledge, is the first attempt to explicitly outline the geomorphic functions of fire-produced CWD in hillslope sediment storage. We propose new terminology to group the geomorphic effects of CWD: *passive storage* through the suppression of tree-throw processes and *active storage* through the production of new CWD that act as barriers to sediment transport. Our field study quantitatively explores active storage and shows that downed logs have the potential to store significant volumes of sediment on hillslopes (>1000 m^3). We also find that sediment storage volumes estimated using established equations likely underestimate the amount of material that can be stored upslope of logs. Finally, we place our storage estimates in the context of long-term hillslope evolution and offer insight into the temporal relationship between CWD and sediment storage.

5.1 | Geomorphic role of fire-produced coarse woody debris

Multiple geomorphic processes are influenced by the CWD produced following fires when damaged trees uproot or snap. We propose that snapping and uprooting trees influence the transport and storage of sediment on hillslopes through two primary pathways. A tree with burnt roots or weakened trunk is susceptible to snapping, resulting in: (i) the prevention or reduced effectiveness of a future tree-throw event; and (ii) the delivery of broken stems to the ground that may act as a barrier to sediment transport and thus store sediment at their upslope extent. Processes such as the domino effect may magnify these effects. Because trees of different species and sizes have varying levels of susceptibility to different fire intensities (e.g., Trouvé et al., 2020), stands that are composed of relatively more fire-resistant species will likely produce different types and volumes of CWD. The likelihood of the active and passive storage scenarios presented in this paper is thus dependent on a variety of factors including topographic setting (e.g., slope), tree characteristics (e.g., species, age, diameter), and fire severity and intensity.

We observed abundant fire-produced CWD with upslope piles of sediment at our study site, consistent with the active storage scenario presented above. In addition, we found a high incidence of burnt and snapped roots and a far higher concentration of stumps as opposed to uprooted trees, indicating that tree-throw processes are partially reduced by fire in this system. The importance of tree-throw as a sediment transport process is well recognized (e.g., Gabet et al., 2003; Phillips et al., 2017; Roering et al., 1999), yet the influence of fire on tree-throw has received little attention (Gallaway et al., 2009). We did not find evidence that fire increases sediment transport by tree-throw in our study system, but a study conducted in the Canadian Rockies showed an order of magnitude increase in sediment transport of post-fire tree-throw compared to pre-fire rates on steep (28°) slopes (Gallaway et al., 2009). These contrasting findings may reflect differences in tree species, soil type, slope steepness, and the type and degree of tree damage, which are all variables likely to influence the likelihood that a tree will break or uproot. Thus, the effectiveness of fire in passive storage scenarios is likely dependent on site- and event-specific conditions.

5.2 | Topographic controls on sediment storage

The volume of sediment stored by logs is controlled at a first order by log abundance, length, diameter, and orientation (Equation 3; Figure 6). We anticipated that log abundance and orientation may additionally be influenced by topographic variables that control resting and rolling patterns. For example, we posited that fallen trees on shallower slopes may be more likely to come to a contour-parallel resting position. However, log orientation showed no dependence on curvature or slope, suggesting rolling or resting patterns do not strongly modulate the storage capacity of CWD in this system.

We also expected that aspect may affect log orientation and storage, potentially due to west-prevailing winds and north–south differences in primary productivity that could influence both tree abundance and fall patterns. We found no clear relationship between log orientation and slope aspect; however, south-facing slopes showed a noticeably greater abundance of logs than north-facing slopes (Figure 8). Slopes with southern aspects in our study catchment tend to be gentler and longer compared to northern aspects (Figure 2), an asymmetry more evident at lower elevations of the catchment. In addition, northern aspects experienced a higher burn severity during the 1998 fire compared to other slope orientations, potentially burning and reducing available CWD. We anticipate that the combination of these effects contribute to the lower abundance of logs on north-facing slopes (Figure 8d), resulting in greater overall storage on southern aspects of the study site.

5.3 | Spatial and temporal controls on sediment storage

Our estimates of potential active sediment storage by CWD are dependent on three important assumptions regarding logs' spatial and temporal capacity to store sediment: (i) logs oriented less than 45° relative to slope contour do not store sediment; (ii) storage is negligible above and below some threshold slope angle; and (iii) remotely digitized logs directly contact the ground surface. The first two assumptions are supported both by our physical modeling experiments and previous work. In tilt table experiments, we found that negligible storage occurred when the log was oriented ≤30° from the direction of steepest descent. A higher threshold was identified in a study following the Mount St Helen's eruption, whereby the majority (>90%) of logs that stored ash and sediment debris were oriented at angles ≥45° (Smith & Swanson, 1987). We applied this 45° orientation threshold in our system, recognizing that it likely results in conservative storage estimates.

That substantive storage may not occur at low slopes (assumption 2) is inconsistent with Equation (3), which predicts that storage is highest at low hillslope gradients if other variables are held constant (Figure 6). Our physical modeling experiments supplied unlimited sediment to obtain observed sediment pile geometries. Achieving maximum-capacity storage at low slope gradients in our study site would also require that storage is not limited by upslope sediment flux. Considering sediment flux is likely slope-dependent on the convex, soil-mantled slopes in our study area, it is unlikely that the volume of sediment required to reach maximum storage capacity will occur at low gradients of our landscape. Indeed, a prior study of sediment storage at the upslope extents of live trees and stumps showed negligible accumulation on slopes with gradients of less than 15° and above 77° (Measeles, 1994), and our tilt table experiment showed the least amount of storage at the greatest slope angle tested (60°). Applying these <15° slope and ≥45° log-orientation thresholds, such that just over one third of digitized logs in this system were determined to store sediment, also likely results in conservative storage capacity estimates.

We were not able to fully assess assumption 3, that the degree of contact between a log and slope surface is complete (i.e., no gaps between log and ground), because this parameter cannot be estimated from aerial photography. We did, however, observe abundant active storage behind logs in our field site, though log jams were most likely to have incomplete contact with the ground. However, these assemblages amass and accumulate abundant fine woody debris, which visibly increases surface roughness and the trapping of sediment, even when some logs are suspended.

While it is unlikely that all downed trees are in contact with the ground at the same time, the process of log decay (and associated contact with the ground) will influence the capacity of logs to store sediment as logs succeed through decay classes (Figure 11). As conceptualized by Maser et al. (1979), when newly downed logs come to rest on the forest floor they may be supported by remaining intact branches (decay class I). Over time these support points are eroded (decay class II) and the log becomes flush with the ground surface (decay class III). At this point in time, sediment storage capacity reaches its maximum, although the amount of storage will also reflect time-varying upslope sediment flux. As logs continue to degrade, sediment storage decreases until the log itself has become part of the surrounding soil (decay classes IV and V). In our system, logs likely persist on the landscape for several decades before being fully mineralized (Brown et al., 1998; Harmon et al., 1986), although timescales of log decay vary with hydroclimatic conditions. Additionally, CWD is likely redistributed across hillslopes before fully decaying, potentially

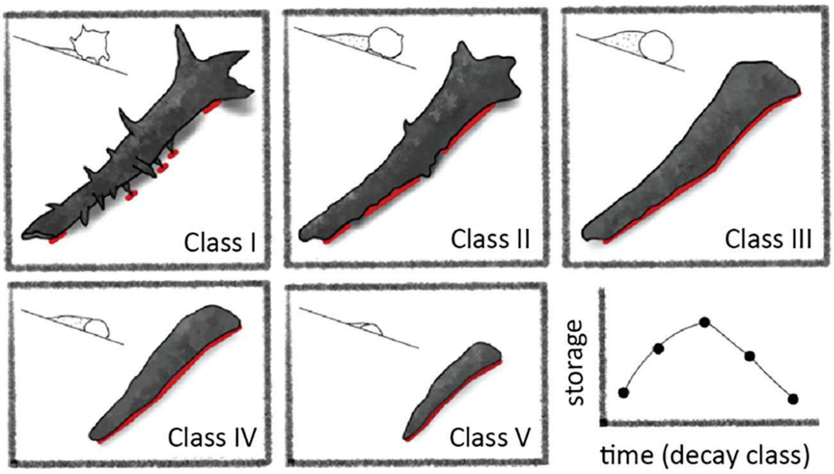

FIGURE 11 The sediment storage capacity of CWD varies temporally during decay. As logs decompose over time (log decomposition decay classes I–III), the degree of ground contact (red lines) initially increases. Storage then decreases with subsequent decay (decay classes III–V) as log density and height above ground decrease. Log cross-sections and associated sediment storage are shown in the top left corner of each decay class sketch. Sketches of decomposition classes are adapted from Maser et al. (1979). [Color figure can be viewed at wileyonlinelibrary.com]

changing position and orientation and, as a result, sediment storage capacity. To our knowledge, the magnitude and frequency of such transience on hillslopes has not been studied. This concept of temporally and spatially dependent sediment storage by logs suggests that our storage calculations likely reflect the longevity and capability of naturally emplaced dams to store sediment and offset erosion rather than the total volume of hillslope storage at a snapshot-in-time.

5.4 | Implications for long-term hillslope evolution

Understanding the landscape-scale impact of sediment storage by post-fire CWD requires a broader understanding of short- and long-term rates of sediment movement and the fire recurrence intervals that drive sediment transport. Robichaud et al.'s (2009) study of post-fire erosion following the 2000 Valley Complex Fires, in neighboring watersheds to our study site, provides a useful context for our storage estimates. The authors measured erosion rates over 3 years using sediment fences installed on steep slopes (average of ~27°) and found that median sediment fluxes of ~8 Mg/ha occurred within the first year following the fires, dropping significantly in the following 2 years (Robichaud et al., 2009). Our estimated sediment storage capacity of logs is ~6–26 times greater than this volume if Robichaud et al. (2009) first-year erosion rate was assumed to occur over a 1 km^2 area.

Several variables not considered in the above comparison should affect the spatial and temporal relevance of our potential storage calculations. Planar hillslopes studied by Robichaud et al. (2009) averaged ~27°, approximately 10° higher than (and in the upper 25th percentile of) average slope gradients in our study catchment. Considering sediment storage potential is negatively correlated with slope angle (Figure 6; Equation 3), and that erosion rates and sediment fluxes are generally positively correlated with slope angle (Roering et al., 2007), we might expect the potential storage capacity of logs in a lower slope system to exceed the volume of sediment eroded following the delivery of fire-produced CWD. Additionally, acknowledging the temporal variability of our potential storage estimates, we do not suggest that rates of post-fire erosion reported in Robichaud et al. (2009) would be necessarily offset by CWD. Instead, we offer this comparison to further contextualize our potential storage estimates and emphasize the thus far unaddressed, possible role CWD could play in sediment storage and transport across hillslopes.

Our estimates of sediment storage potential in Rye Creek suggest that logs may act as significant contributors to sediment disconnectivity in mountain catchments. To further place potential storage in the context of longer-term evolution of the landscape, we use a range of ^{10}Be-derived catchment-averaged erosion rates from landscapes in Idaho (Kirchner et al., 2001) and the Sierra Nevada (Riebe et al., 2001) with similar granodiorite lithology, relief, and semiarid climate. Applying our upper and lower estimates of catchment sediment storage (3500 and 14 000 m^3/km^2) based on log diameters between 0.25 and 0.5 m, and an assumed average erosion rate ranging between 50 and 100 mm/ky, we calculate that the storage capacity of logs in our study area represents the equivalent of between 35 and 280 years of soil production. These storage timescales exceed those shown for sediment trapped upslope of live vegetation in the San Gabriel Mountains, where yucca was estimated to accumulate the equivalent of a minimum of 30 years of soil production (Dibiase & Lamb, 2013), further underscoring the importance of logs as important sites of sediment storage following both isolated and repeat disturbance events.

In landscapes shaped by repeat fire events, the timing and manner of sediment storage in our active scenarios would likely be influenced by residence time of logs on hillslopes and time between subsequent fires. The decay of CWD on hillslopes is a function of size, species, and local environmental conditions (Harmon et al., 1986). If we consider the time it takes for logs to completely decay and lose sediment storage capacity compared to the fire return interval for a landscape, three scenarios are likely to ensue. First, if the residence time of logs is shorter than the fire return interval, sediment stored by logs will be incrementally released downslope as logs decay. Second, if logs are still intact and actively storing sediment at the time of a subsequent fire, stored sediment will be released abruptly if the fire were severe enough to combust and remove existing CWD. The third scenario involves a mix of the previous two where some CWD would have completely decayed while some would be actively storing sediment at the time of a subsequent fire. This final scenario is most likely in our study system, considering that CWD following a fire is not delivered in a single pulse, though homogeneity in stand age and species could trend responses toward either end member scenario (Bendix & Cowell, 2010).

Regardless of the relationship between fire return interval and log residence time, sediment storage by logs is not a single, event-based process but rather a process that continuously impacts delivery and storage of sediment on hillslopes. Passive storage scenarios as described here are similarly suggested to have persisting effects on hillslope evolution. Tree-throw is a dominant process of hillslope sediment transport in forested landscapes, so the prevention of tree-throw processes via stem snapping following fires could retard a primary driver of sediment movement. Much research has focused on post-fire sediment erosion on hillslopes and has shown most erosion occurs within the first few years following a fire (Moody et al., 2013). Our results suggest that the enduring effects of fire-produced CWD on hillslope sediment storage and evolution may be undervalued. These methods and insights can be applied not only to post-fire environments but also other landscapes prone to disturbance-driven changes in CWD (e.g., windthrow events). However, not all events can be expected to have similar impacts on CWD delivery, sediment storage, and landscape change (Peterson & Pickett, 1995). In addition, a landscape might experience multiple types of disturbances, and antecedent conditions may mitigate the impacts to live vegetation, delivery of CWD, and subsequent stand structure (Kulakowski & Veblen, 2002).

5.5 | Directions for future research

We identify three future research directions to advance the understanding of the geomorphic role of CWD on hillslopes in fire-affected landscapes. First, future research should address CWD and sediment storage dynamics, specifically, field-validated measurements of frequency, longevity, and redistribution of CWD subtypes on hillslopes. We suggest conducting field surveys to inventory logs and stumps at multiple intervals following fires and tracking movement of logs through field or remote surveys. Numerical, physical, or other modeling techniques should be used to refine maximum sediment storage scenarios behind log barriers with the addition of variables affecting storage potential such as sediment cohesion, particle size, soil type, erosion rates, and runoff.

Second, future work should address the impact of disturbance properties, such as fire severity, intensity, size, and recurrence intervals, on sediment storage potential. The degree to which these variables affect CWD input, properties, and persistence should be evaluated alone and in combination in a variety of forest types and landscapes. We anticipate the importance of passive and active storage to vary with forest type, tree species, stand age, and fire properties. For example, based on our assumptions we should expect that an old-growth forest would experience higher frequency and rate of active sediment storage by logs compared to a younger stand due to the average size of trees.

Finally, it is critical that this work be explored across multiple spatial and temporal scales across different landscapes. The geomorphic role and importance of CWD would likely change in response to different erosion rates, climate, sediment transport processes, and soil cover. Sediment storage by CWD may have very little influence in short- and long-term sediment budgets in landscapes evolving primarily through landsliding as opposed to those driven by diffusion. Additionally, sediment storage by CWD may play an important role in sediment connectivity in small watersheds but be obscured by other processes in larger catchments.

6 | CONCLUSIONS

While the geomorphic effects of coarse woody debris in streams have been rigorously examined for decades, the influence of CWD on hillslopes has received little attention. Our study provides new information clarifying the relationship between wildfires, sediment storage and transport, and CWD and highlights the significant capacity for downed trees to store post-fire sediment. First, we provide a conceptual model to further ongoing investigations into hillslope connectivity, specifically highlighting the role of wildfire in producing CWD that act as active barriers to sediment transport and reducing and/or passively preventing tree-throw processes. Second, using high-resolution topographic data and aerial photography, we quantify the presence of CWD and its potential influence on active hillslope sediment storage at the catchment scale. Last, we compare estimates of storage potential to both short-term, post-fire sediment fluxes and long-term landscape-scale erosion rates.

Our results suggest that the volume of coarse woody debris that is present on hillslopes following fires can not only be substantial but could act as highly capable barriers to sediment movement, limiting rapid post-fire sediment movement that occurs in the absence of downed trees. We find that CWD can potentially store large volumes of sediment for several years following severe erosion events. Our study only considers active storage by logs but can be expanded by explicitly incorporating passive storage due to reduced or prevented tree-throw processes. We suggest that these fire–vegetation–sediment interactions play an important role in hillslope evolution and the delivery of hillslope materials to streams in fire-prone, soil-mantled landscapes. Our physical modeling experiments and field study show that potential sediment storage upslope of logs is an important and complex process that invites further study.

AUTHOR CONTRIBUTIONS

Adams led data collection, methodological development, and writing. Adams and Dixon interpreted the data. Dixon and Wilcox provided funding and supervision. All authors participated in conceptualization and editing.

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CONFLICT OF INTEREST STATEMENT

The authors have no known conflicts of interest.

DATA AVAILABILITY STATEMENT

All spatial data are publicly available through OpenTopography.org.

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