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Key Points:

- A 20-year instream wood study of two headwater streams demonstrates that near-channel logging significantly reduced instream wood loads
- Wet windstorms and steep slopes were associated with wood inputs from standing trees, but rates varied between streams and over time
- Piece characteristics, the surrounding density of wood pieces, and discharge metrics influence wood entrainment and displacement lengths

Supporting Information:

Supporting Information may be found in the online version of this article.

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Large Wood in Small Channels: A 20-Year Study of Budgets and Piece Mobility in Two Redwood Streams

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Abstract Large wood (LW) influences geomorphic and ecological processes. However, most field data sets describing LW dynamics are conducted over the span of only a few years. We present a unique long-term data set from northern California, USA of LW volumes, inputs, and transport in two small headwater streams, the North Fork (NF) and South Fork (SF) of Caspar Creek. We used data collected approximately every 2 years from 1998 to 2018 to assess how LW budgets change over time between catchments, what factors influence inputs from standing trees to the streams, and controls on LW piece mobility. We find that the SF, which experienced stream-side logging and instream wood removal in the 1970s, continued to have lower LW volumes (range of 101–153 $m^3\ km^{-1}$ over the 20-year period) compared to the NF (range of 297–313 $m^3\ km^{-1}$), which experienced logging in the 1980s but with buffer strips left near the channel. If current trends continue, it will likely take ∼100–200 years from the time of logging for the SF to reach NF instream wood volumes. We show that windstorms combined with precipitation events, very high winds, and hillslope steepness are strongly associated with LW piece inputs from standing trees. LW moves infrequently in the channel, with piece characteristics, the number of wood pieces per meter surrounding an LW piece, and discharge metrics influencing LW entrainment and displacement lengths. Our data set provides strong support to previously identified controls on LW dynamics in streams while also capturing variability over a 20-year period.

Plain Language Summary Wood in rivers affects both physical processes and ecological processes, such as habitat creation. Long-term field data sets are important for understanding how the amount of wood in streams changes over time, how standing trees enter the channel, and how wood moves. However, most field data on wood in streams were collected in the span of just a few years. We present a field data set of repeat wood surveys in the channel for two streams in northern California, USA. Wood and wood inputs were measured every 2 years over a 20-year period. With these data, we demonstrate that intensive logging near the stream on the South Fork of Caspar Creek from 1968 to 1973 is still resulting in lower wood volumes in that channel compared to the North Fork of Caspar Creek, which was logged further from the channel from 1988 to 1991. The frequency of winter storms and the steepness of adjacent hillslopes also influence inputs of wood from standing trees. Wood moves relatively infrequently, but the size and shape of wood pieces and the frequency of high flow events impact whether a wood piece moves and how far it moves. Our results can inform management decisions about wood in rivers.

1. Introduction

The dynamics of large wood (LW) in river systems influence both geomorphic and ecological processes (Wohl et al., 2019). For example, LW influences bedform and bar development (Abbe & Montgomery, 1996; Gomi et al., 2003), channel planform (Bertoldi et al., 2013; Piégay & Gurnell, 1997; Wohl et al., 2012), and sediment storage (Richardson et al., 2020; Welling et al., 2021; Wohl & Scott, 2016). LW is important for habitat creation for fish and other biota in rivers (Fausch & Northcote, 1992; Flores et al., 2017; Jones et al., 2014), and is an important organic carbon stock within the river corridor (Lininger et al., 2017; Seo et al., 2008; Sutfin et al., 2016). Because wood has been removed from many river channels due to logging and for navigation (Wohl, 2014), current restoration practices often involve adding LW to stream channels to promote habitat formation and ecological functioning of streams (Roni et al., 2015).

Wood budgets, which account for the inputs, outputs, and changes in storage of a given river reach (Benda & Sias, 2003; Martin & Benda, 2001), can be used to predict and understand the effects of forest management on LW loads and inform understanding of LW sources and mobility. However, records and measurements of

LW are usually of short duration, limiting insight that can be gained regarding changes in LW loads over time and LW mobility within river systems (Wohl, 2017). We describe a 20-year tagged-wood study with surveys conducted approximately every 2 years in two streams within the Caspar Creek Experimental Watersheds, USA that have contrasting management history and wood loads. We know of only one other published study (Reid & Hassan, 2020) that measures wood over a similarly long time period at high temporal resolution, although longer-term data sets are becoming more common (Iroumé et al., 2020; Máčka et al., 2020; Picco et al., 2021; Reid & Hassan, 2020; Wohl & Goode, 2008; Wohl & Scamardo, 2021). Our data provide insight into how past forest management and environmental factors control the amount and distribution of LW in these channels. We also assess controls on LW inputs and the conditions under which LW is mobilized, relating LW mobility and the distance LW travels in the stream to LW characteristics and discharge records.

Wood budgets have been used to understand the influence of disturbances such as wildfire and mountain pine beetle infestations in changing patterns of wood recruitment, output, and storage in channels (King et al., 2013) and to assess the long-term influence of human disturbance and wood removal from channels (Boivin et al., 2017; Reid & Hassan, 2020). Logging can result in lower LW loads in channels and on floodplains, with varying lengths of time required to return to prelogging levels (Benda & Bigelow, 2014; Reid & Hassan, 2020; Scott & Wohl, 2018). Understanding the controls on LW input rates can also provide information to managers concerned with maintaining wood supplies to channels in managed forests and predicting the time required for channels to recover predisturbance LW loads (Murphy & Koski, 1989; Stout et al., 2018).

LW inputs to a stream reach occur via individual tree mortality and toppling; mass recruitment events such as wind storms, debris flows, and landslides; bank erosion; and beaver activity (Iroumé et al., 2020; Máčka et al., 2020; Martin & Benda, 2001; Wohl, 2017). The distance that LW is sourced from the channel varies with respect to input mechanism (e.g., between bank erosion and wind-mediated recruitment) and tree stand age and height (Benda & Bigelow, 2014; Bragg & Kershner, 2004), and recruitment may be higher on steeper slopes relative to shallower slopes (Natural Resources Management Corporation, 2003). In streams where hillslopes are highly connected to channels, recruitment via hillslope processes and mass movements can be substantial (Hassan et al., 2005; Komori et al., 2021; Madej, 2010). Forest harvesting locations adjacent to riparian corridors can potentially increase the impact of wind storms on LW recruitment by exposing unharvested trees to greater wind loads and increasing recruitment (Bahuguna et al., 2010). However, the interactions between tree species, recruitment mechanisms, and management histories have not been fully explored, particularly over longer time scales.

Once LW is recruited to channels, wood is lost due to transport downstream, overbank deposition, and decay, breakage, and attrition of individual pieces (Benda & Sias, 2003; Wohl, 2017). One aspect of the wood budget that is particularly difficult to constrain is the transport of wood within the channel, in part due to the lack of long-term field studies that go beyond measurements of movement from an individual flood event (e.g., Schenk et al., 2018). Previous work has indicated that wood piece size in relation to channel morphology influence wood mobility (Braudrick & Grant, 2001; Braudrick et al., 1997; Gurnell et al., 2002). For example, piece length relative to channel width and piece diameter relative to channel depth control whether wood pieces remain stable or are moved (Dixon & Sear, 2014; Iroumé et al., 2018; Virginia Ruiz-Villanueva et al., 2016; Wohl & Goode, 2008). Buried pieces, pieces with rootwads, and pieces in jams (i.e., wood accumulations) are less likely to be transported downstream compared to other pieces (Dixon & Sear, 2014; Iroumé et al., 2018; Wohl & Goode, 2008). Studies of wood mobility have recently begun to relate wood flux and movement to discharge records, finding that entrainment and wood flux are greater above a certain threshold discharge or as the frequency of high flows increase (Iroumé et al., 2018; Kramer & Wohl, 2014; Ravazzolo et al., 2015). More work is needed to understand thresholds for LW movement in a variety of channel types, and many studies incorporating LW mobility and transport lack detailed information on the distance that individual pieces travel over multiple time steps. As numerical models of LW transport continue to be developed (e.g., Kang et al., 2020; Ruiz-Villanueva et al., 2014), there is a greater need for better and longer-term field measurements for model construction and validation.

We present wood budgets at approximately 2-year intervals over a 20-year period based on a tagged-wood study in the Caspar Creek Experimental Watersheds in northern California, USA. We also use statistical models to examine factors affecting input rates over time and assess wood piece mobility and factors controlling the distance moved within the channel for individual pieces. Our study is located on the North Fork (NF) and South Fork (SF) of Caspar Creek. The SF was heavily logged from near-channel roads without the use of buffer strips

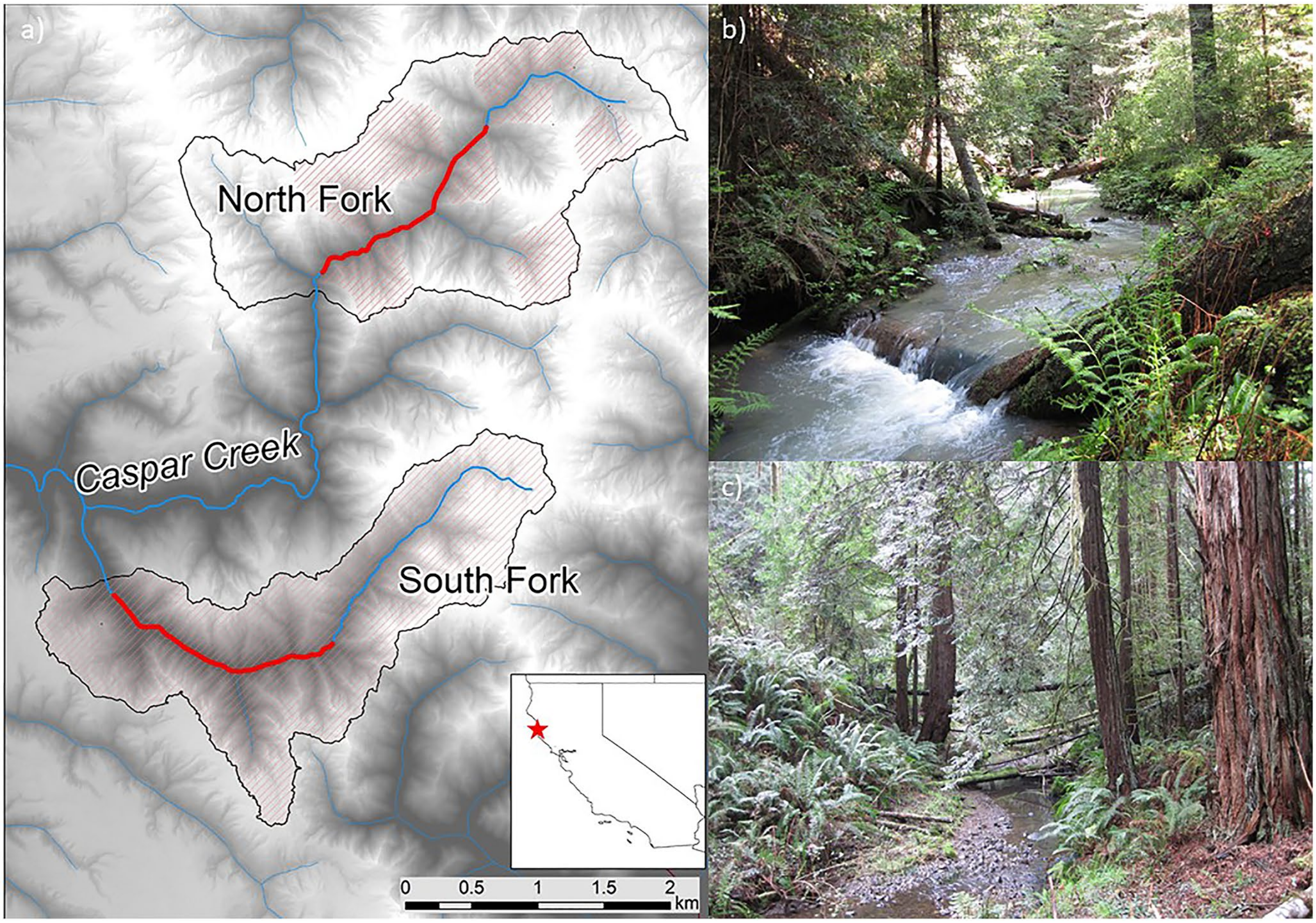

Figure 1. The North Fork (NF) and South Fork (SF) of Caspar Creek (a) with the study reaches in red, blue lines showing streams, and inset showing location in California, USA. Locations of clearcuts in the NF are shown with light red hatching, and light red hatching in the SF indicates logging throughout the watershed (see text for details). Channel photos of (b) the NF during a moderate winter flow and (c) the SF at low flow.

in the early 1970s, and wood was removed from the channel. In contrast, the NF was logged from upslope roads with buffer strips left along the channel in the late 1980s and early 1990s, providing a comparison of wood budgets between streams with differing near-channel logging intensity. Our research questions include (a) how does the LW budget change over time in catchments with varying land-use histories? (b) what factors (e.g., stand attributes, windstorms, discharge) strongly influence LW input rates from standing trees to the streams? and (c) how do piece characteristics, stream geomorphology, and discharge influence entrainment and the displacement length of LW in the channel?

2. Study Area and Methods

2.1. Study Area

The two study reaches are on the mainstems of the NF and SF of Caspar Creek in the Jackson Demonstration State Forest in Mendocino County, California (Figure 1), and are located ~7 km inland from the Pacific Ocean. The drainage areas are 4.79 and 4.17 km^2 for the NF and the SF, respectively (Richardson et al., 2021b). Climate in the region is Mediterranean, with relatively dry summers with fog and winter storms from moist air moving in from the Pacific (Henry, 1998). Mean annual precipitation is 1,170 mm, and almost all precipitation is rainfall, with most of that occurring between October and April (Richardson et al., 2021b). The drainages are underlain by the Coastal Belt of the Franciscan Complex, which contains graywacke, sandstone, siltstone, mudstone, shales, and conglomerate (Dymond et al., 2021; Jennings & Strand, 1960).

The NF and SF study reaches are 1,843-m and 1,914-m long, respectively, and the downstream end of each reach is just above a weir pond. Slopes within the streams range from 1% to 3%, and mean bankfull channel widths range from ∼6 m at the downstream ends to ∼4 m at the upstream ends of the study reaches. Both reaches have 1-m to 10-m-wide terraces 0.7–1.5 m above the low-flow channel along one or both banks for 90%–95% of the reach length. Both channels also have small in-channel vegetated bars which are flooded at less-than-annual flows. Valley wall slopes average about 30% in the SF and 35% in the NF. Stream inventories in 1995 noted wood accumulations (generally large logjams) at 11 locations in the NF study reach and 3 in the SF reach (Watershed Stewards Project, 1995a, 1995b). There are also many wood pieces not within jams. In 2016, 54% and 43% of pieces were located within jams on the NF and SF, respectively, using a definition of a jam as three or more pieces in contact that accumulated additional pieces. Major anthropogenic changes in forest structure and channel wood in both the NF and SF watersheds began in the late nineteenth century when the original coast redwood forests were logged and burned. Streams were cleared of wood and other physical obstructions at that time to facilitate log conveyance (Napolitano, 1998), sometimes through the use of splash dams.

In the SF watershed, after almost a century of regrowth, roads for hauling logs were built along the mainstem in 1968, followed by removal of 65% of the stand volume in 1971–1973. Logs were hauled by tractor to roadside landings, with minimal stream protection, as was common before the passage of California's Z'Berg-Nejedly Forest Practice Act of 1973. The combination of near-stream roads and tractor skid trails left much of the watershed impacted, including impacts adjacent to the channel. Logging plans (Jackson State Forest, 1970) included cutting scattered, residual old-growth Douglas-fir (*Pseudotsuga menziesii*) and redwood (*Sequoia sempervirens*). Krammes and Burns (1973) mention fill slope failures, erosion at bridge crossings, stream cleaning, and tractor work in the channel during and after roadbuilding and logging. Instream wood removal during logging in the 1970s was suspected to be the cause of lower LW volumes on the SF in the mid-1990s (Surfleet & Ziemer, 1996). By 2004/2005, a standing tree inventory by Caspar Creek research staff in 2004 and inventory plots showed channel-adjacent stands along the SF to be dominated by redwood, with a significant component of Douglas-fir (∼15% of the basal area), along with western hemlock (*Tsuga heterophylla*), tanoak (*Notholithocarpus densiflora*), and red alder (*Alnus rubra*), particularly near the stream channel and along roads. Grand fir (*Abies grandis*) is also present in the stands but not in our sample plots. Mean dominant and codominant tree heights (24 m for Douglas-fir and 31 m for redwoods) were consistent with calculated mean canopy heights of 20–30 m from a 2003 LIDAR flight (U.S. Geological Survey, 2014).

In the NF watershed, logging from 1988 to 1991 primarily occurred in small clearcuts, with 45–60 m protective buffer strips along the channel; there was some, but minimal, cutting within these buffer strips. These buffers are on one or both sides of ∼70% of the length of the NF study reach. The remaining area along the stream outside of the buffers was entirely within uncut control stands. Blowdown from buffer strips and uncut forest added significant pulses of wood to the channel between 1990 and 1994 and during windstorms in water years (WY, 1 August–31 July, which is the water year definition used in the Caspar Creek watersheds) 1995 and 1996. Channel-adjacent stands mapped and inventoried between 1994 and 1998 (Reid & Hilton, 1998) were dominated by redwood, but with more Douglas-fir than in the SF (almost 40% of the basal area). Western hemlock, grand fir, and tanoak were also present in the NF, but alder was not. Dominant and codominant tree heights, based on measurements of standing and blown-down trees, averaged 55 m for Douglas-fir and 49 m for redwood, with LIDAR canopy heights of 50–54 m. These taller average heights reflect the more limited impact that logging had on stream-adjacent stands in the NF due to the buffer zones and the areas adjacent to the stream that were not cut.

2.2. Data Collection

A common definition of LW in wood research are pieces >1 m in length and >10 cm in diameter (Wohl et al., 2010), but our surveys included LW > 2 m in length and >20 cm in diameter in or near the channel due to the large size of the trees in our study area. LW pieces were tagged in the 1,843 m section of the NF and the 1,914 m section of the SF starting in 1998. Each of these two reaches is also divided into 18 subreaches that are ∼100 m long, with breaks based on management and geomorphic features, such as tributaries, large persistent jams, and near-channel roads. All pieces have an entry date range (down date group) assigned to them, with pre-1998 entry dates determined through records from previous work in the watersheds as well as visual cues and decay classes, as described in Text S1 in Supporting Information S1. For example, during the initial tagging, logs that entered the NF in WY 1996 and newly entered logs (WY 1997 and 1998) were identified based on flagging and notes from a full-channel down tree survey in December 1995 (Reid & Hilton, 1998), other poststorm surveys, and through estimating ages of the downed trees by decay class (see Text S1 in Supporting Information S1). In the SF, which did not experience a large 1995 blowdown, there were fewer records, and 1995 inputs were identified using a combination of factors, including visual cues and decay class (see Text S1 in Supporting Information S1). In both reaches, tagged pieces included in this data set are pieces that had at least 2 m of length with a minimum diameter of 0.2 m within the extended channel, defined as being in the channel and within 1 m outside of the channel banks on each side of the creek. Standing stumps and live trees in and partly in the channel were not included. Pieces were inventoried approximately every 2 years. Each log has a unique entry id assigned at the time the piece entered the channel. The NF was fully inventoried in 1998, 1999, 2002, 2004, 2006, 2008, 2011, 2014, 2016, and 2018; the SF was fully inventoried in 1998, 2000, 2002, 2004, 2006, 2008, 2011, 2014, 2016, and 2018. New pieces were mapped and measured but existing pieces not checked during input-only surveys in both forks in 2005, 2010, and 2013. Measurements of piece location were taken as the center of the piece length within the extended channel.

Piece characteristics measured during mapping are listed in Table 1 and fully described in Text S2 in Supporting Information S1. At each full inventory, new pieces were identified, and previously tagged pieces were checked for movement, breakage, and other characteristics. New and changed pieces were tagged or retagged if needed, measured, and mapped. Data were collected on input mechanisms and source trees for new pieces, and on change or loss mechanisms for gone or changed pieces, and that information was used to classify pieces into budget groups (see Section 2.3). Table 1 summarizes piece data collected during surveys as well as data collected on subreaches, on channel-adjacent stands, and for each interval between surveys. Across the surveyed years, some piece data were missed due to changes in survey protocols over time. These missing data were reconstructed using the detailed maps that were created at the time of each survey and other techniques, which are described in Text S1 in Supporting Information S1.

Data used for input analysis also included channel-adjacent forest stand and geomorphic data for the subreaches (Table 1). Channel-adjacent stands for each subreach were identified in GIS as the area within two polygons extending 30 m out from each bank (Figure S1 in Supporting Information S1). Those source areas were overlaid on lidar-based topography and canopy heights calculated from U.S. Geological Survey 2003 lidar point clouds (U.S. Geological Survey, 2014), vegetation type mapping (USDA Forest Service, 1998, 2007), field terrace mapping, a scanned and rectified 1975 air photo of the SF, and NF cut boundary mapping to get subreach source area attributes (Figure S1 in Supporting Information S1). Geomorphic characteristics of the subreaches, including the subreach slope and average channel width, were used in wood mobility analyses and calculated from channel mapping and longitudinal surveys conducted in 2001 and 2017 in the SF and in 1991 and 2009 in the NF, and cross sections surveyed approximately every 2 years on both reaches. Additional details on the geomorphic characteristics are included in Text S2 in Supporting Information S1.

We also included data on wind events and discharge for each time interval between surveys. Although the time intervals were different between the full survey years (used for budgets and piece movement) and the input survey years (full surveys plus input only years, used for input analysis), the same interval data were collected for each. Data were adjusted for the length of time between surveys to look at weather and discharge controls on piece movement and piece inputs (Table 1). Input counts and volumes in each interval were divided by interval length for comparison; interval lengths were described in winters, where a full winter is from 1 November to 1 May (181 days), since winters are when most storms and most LW inputs occur in the study area. Winters are roughly equivalent to years, except for intervals including the NF 2002 survey, which was completed in early February. We analyzed flow data from the NF and SF (Richardson et al., 2021a, 2021b) and calculated flow metrics, including peak discharge and the frequency of discharges with different magnitudes (Table 1). We used wind speed data from National Buoy Data Center Ocean buoy 46014, located offshore about 25 km SW of the Caspar Creek watershed (National Oceanic and Atmospheric Center, 2021) to calculate a reference maximum wind speed and counts of winter days with high winds (maximum gust in the top 1% of all daily maximums) in each interval. Because windthrow often occurs when high winds combine with saturated soils (Mitchell, 2013), we also combined wind and flow data to get counts of periods with both storm flows (when soils would likely be saturated) and high winds (see Text S2 in Supporting Information S1 for details).

Table 1
Description of Data Collected for Each Surveyed Piece at Each Interval, for Each Subreach and Channel-Adjacent Stand, and for Each Time Interval

Variable	Description
Data collected during survey	
l_{tot}	Total length of the piece (m)
l_{chan_ex}	Length of the piece within the extended channel (m)
Diam	Midpoint diameter (m)
Angle to channel	Azimuth of the piece relative to the azimuth of the channel, ranging from 0° to 90°
Species	Red alder (AL), unknown conifer species (CON), Douglas-fir (DF), unknown nonredwood (UNNR), grand fir (GF), western hemlock (HL), coast redwood of unknown age (RW), old-growth redwood (RWO), second-growth or third-growth redwood (RWY), tanoak (TO), and unknown (UNK)
Position	Piece location relative to the channel: located entirely in the channel (inchannel), partially in the channel (partiallyin), spanning or suspended above the channel at or below the bankfull channel (span), on the bank with no portion in or above the channel (bank), or spanning the channel well above high flow levels (highspan)
Rootwad	Does the piece have a rootwad? Yes or no
Hinged	Is the piece hinged (broken and bent but partly attached) to another piece? Yes or no
Vbar	Is the piece on a vegetated bar or active floodplain? Yes or no
Buried	Is the piece partly buried in the bed or banks? Yes or no
Jam	Is the piece a part of a jam, defined by a grouping of three or more pieces that have demonstrated trapping of additional pieces? Data on jams are available from 2008 to 2018, but not prior to 2008
Budget group	How has the piece changed since last check? Same; new (inputs, by mechanism); gone, too small, or otherwise no longer in data (losses, by mechanism); or changed but still included (net change). See text for details
Displacement length	Distance moved downstream along the channel from last survey (m)
Live	For newly entered trees, was the tree alive or dead when it fell or broke (live, snag, probably live, probably snag, recently dead)?
Downm	How did the tree fall? (windthrow, wind-snapped, landslide, bank erosion, hit by another tree, unknown)
DDG1	Down date group (e.g., channel entry date range), detailed (includes NF inputs during logging and inputs to both forks 1995–1996 and 1997–1998, plus three intervening years when all new pieces were tagged)
DDG2	Down date group (e.g., channel entry date range) for budgets, includes pre-1998 groups and complete survey years from 1998 to 2018
Distb	Distance from bank for standing tree inputs (I_t) (m)
Subreach data	
Pc_perm	Density of pieces in the subreach, the number of pieces per meter
MnChW	Mean width of bankfull channel of the subreach (m)
Slope	Average channel slope of the subreach (%)
Channel-adjacent stand data for each subreach	
PctTall	Percent of source area canopy >35 m tall (%)
PctRWW	Percent of total nonclearcut area classed as redwood-dominated in both 1998 and 2007 vegetation mapping
DistMar	Mean distance to the nearest clearcut margin (NF) (m)
PctSteep	Percent of source area with slope >35%
MnTerW	Mean terrace width in the subreach, calculated as the mapped terrace area/subreach length
Time interval data	
Yrs95	Years since 1995: Postwindstorm surveys and stand mapping in spring 1995 and a whole channel survey in the NF in December 1995 identified new inputs that were subsequently tagged. This gave us our first input year and time reference for input analyses
PeakQ	Maximum discharge that occurred in the interval between field surveys ($m^3\ s^{-1}$)
PkA	Number of periods with stage > a 1-year recurrence interval discharge for each catchment normalized by the number of winters between field survey. This stage is equivalent to >0.88 m on the NF and >0.91 m on the SF

Table 1
Continued

Variable	Description
PkSD	Storm discharge days (number of days with weir stage >0.61 m) normalized by the number of winters between field surveys
WM	Maximum windspeed offshore, m/s within the interval between field surveys
WWS	Wet winter storm count: number of discreet periods with max windspeed in the top 1% of all days and stage >0.61 m at the weir, normalized by the number of winters

2.3. Wood Budgets

To construct wood budgets for the NF reach and SF reach for each interval between two complete surveys, we calculated the volume of each piece of wood as a cylinder, using midpoint diameter (*d*) and length within the extended channel (l_{chan_ex}) for the portions of the pieces that met the minimum size criteria. For odd-shaped pieces, we estimated the average cross-sectional area by measuring the width and thickness of the pieces, and then multiplied the cross-sectional area by piece length to determine volume.

For each survey interval, budgets were constructed by determining inputs (*I*), losses (*L*), and the difference between current and previous year volumes for pieces that were still included but had changed either due to natural processes or trail work (net change (*N*)). Small trees that were too small to include when they first fell (mostly redwoods) sometimes remained alive after they fell into or across the channel; some of these became inputs due to ingrowth (I_g) if they became large enough to tag through growth. We also included an estimate of untagged gone (U_g), which is the volume missing from the budgets because of a change in tagging criteria. As described in Hilton (2012), the 1998 tagging included most new pieces from WY 1995 to 1998 but only large older pieces, so wood and pool maps were used to estimate the volume of smaller pieces that were untagged in 1998 and gone in later surveys (see Text S2 in Supporting Information S1).

We calculated budgets for each reach (one on the NF and one on the SF) for each interval between full inventory years as

$$V_{(i)} = V_{(i-1)} + I_t + I_s + I_m + I_d + I_u + I_g - L_o - L_g - L_b - L_s - U_g + N_m + N_t$$

where

$V_{(i)}$	total volume within the extended channel at time *i*
$V_{(i-1)}$	volume at the end of the previous interval
I_t	Inputs from standing trees or stumps
I_s	inputs from valley bottom storage (bed or banks)
I_m	inputs from unknown older pieces, usually moved from elsewhere
I_d	inputs from previously down pieces on hillslopes
I_u	inputs from upstream (in-channel transport)
I_g	ingrowth (down live trees that grew large enough to be tagged)
L_o	outputs downstream (in-channel transport)
L_g	lost pieces (gone and missing)
L_b	losses to breakage/attrition (now too small to include)
L_s	losses to storage (deposited off-channel or buried in bed or banks)
U_g	estimated volume not tagged in 1998 but gone by 1999/2002 (NF) or 2000 (SF) due to storms
N_m	net change in volume of moved/broken pieces that remain in the census; pieces can move further into the channel and thus gain volume, or lose volume by breakage, burial, or moving further out of the channel
N_t	net change in volume from human activity, usually trail work

2.4. Standing Tree Input Analyses

Our input analyses focused on analyzing controls on inputs from standing trees, I_t. We computed cumulative distribution curves of source distance by tree input counts (number of individual trees contributing at least one taggable piece) and volumes for all nontrail-work inputs with known sources (91% of NF inputs, 97% of SF).

To analyze factors associated with input rates, we developed regression models to predict input counts per subreach per detailed time interval, DDG1 (the full survey years plus 1995–1996, 1997–1998, and input only years). Wind and flow data were summarized by these detailed time intervals. Inputs were assigned to source subreaches based on GIS mapping of the source tree when available (about 75% of NF inputs and less than 10% of SF inputs). For unmapped sources, we assumed the tree was adjacent to the channel subreach in which the piece (or the furthest-upstream piece if a tree contributed multiple pieces) was found, except for a few pieces with notes on field data sheets indicating they were upstream of their sources.

The SAS program (SAS/STAT software Version 9) PROC GLIMMIX (Littell et al., 2006) was used to construct generalized linear mixed models (Gelman & Hill, 2006) for predicting the number of inputs into each subreach in each interval. A Poisson distribution was assumed for NF inputs; in the SF, a negative binomial distribution was used after determining that the variability in the data was too large for a Poisson distribution. Models were developed for the following response variables: all inputs for the NF, all inputs for the SF, and post-1998 inputs only in the NF and SF to separate patterns associated with very high windstorms that occurred in the winters of 1995 and 1996, shortly after the completion of logging in the NF. Model formulation included adjustments for interval length (number of winters) and subreach lengths. Subreach was treated as a random effect to account for the multiple surveys over time in the same subreach. Potential predictor variables included the subreach and interval data in Table 1, with a few additional variables that were removed due to multicollinearity (see Text S3 in Supporting Information S1). All predictor variables considered (PctTall, PctRWW, DistMar (NF only), PctSteep, MnTerrW, Yrs95, PeakQ, WM, and WWS) were treated as fixed effects. The best model for each response variable was chosen from all possible 1 to 3 variable models based on Akaike's Information Criteria, adjusted for small sample sizes (AICc; Burnham & Anderson, 2002). Models were limited to 1–3 variables to limit the number of models to compute and compare. We also report the sum of the Akaike weights from all possible models for each response variable to rank the importance of predictor variables (Wagenmakers & Farrell, 2004). Additional information regarding the model formulation is included in Text S3 in Supporting Information S1.

2.5. Wood Mobility

To analyze wood mobility, we computed the displacement length (i.e., the distance moved downstream along the channel) for each piece within each time interval and then normalized the displacement length by the number of winters in each time interval. For each displacement length observation, we linked the piece characteristics at the start of the time interval to the observation. Because piece characteristics were only measured at the start and end of each time interval, piece characteristics at the start of the time interval provide the best understanding of the relationship between displacement length, piece characteristics, and other metrics that would likely be influential for piece movement, even if the piece was modified during displacement. We did include one piece characteristic from the end of the interval in a specific case: if a piece broke into two pieces and one piece moved during the interval, we added the broken-off piece to the data for the previous survey, with a total length based on its postmovement length. Any negative calculated displacement lengths (usually because a piece lost a downstream section) were converted to 0 and all calculated lengths <0.3 m were checked using field sketches and photos and adjusted if needed because small recorded displacement lengths are likely subject to greater error. We also used geomorphic characteristics of each subreach and discharge observations by intervals. Our data set for the displacement length observations thus included a distance moved within the interval as the response variable, the piece characteristics at the start of the interval, the geomorphic characteristic by subreach at the start of the interval, and the discharge metrics computed for the interval.

We plotted cumulative distribution functions for displacement length observations by species, position, and other categorical variables. We also conducted regression analyses to explore the influences on displacement length observations while controlling for variability in multiple predictor variables. Because a majority of observations were of no movement (displacement length = 0), we used two different regression models to assess controls on both entrainment (whether or not a piece moved) as well as the displacement length (nonzero observations). We used a logistic regression to assess the odds of movement (entrainment) versus no movement, with clustered standard errors to account for repeated measures (multiple observations on individual pieces; Zeileis et al., 2020). We used a mixed effects linear regression model with multiple covariates and a log-transformed displacement length response variable to assess controls on displacement length, with the ID of each piece as the random effect. Numeric predictor variables included piece diameter, piece length/channel width, slope, the piece angle to channel, the density of pieces in each subreach (number of pieces per meter), the number of peak storm days (PkSD), and the number of annual storms (PkA). Categorical predictor variables included whether the piece had a rootwad, was buried, located on a vegetated bar, or was hinged, as well as the piece position. We affirmed model assumptions with plots showing heteroscedasticity and normality of residuals.

3. Results

3.1. Wood Budgets

Wood volume inputs and losses for the NF and SF for each interval are shown in Figure 2 and Table S1 in Supporting Information S1, along with total volume in each interval by piece input date. Input volumes on the NF ranged from 7.00 to 17.81 $m^3 km^{-1}$ per year over the 20-year period, while SF inputs ranged from 0.66 to 10.53 $m^3 km^{-1}$ per year with a general increasing trend over time (Figure 2). We report volumes in $m^3 km^{-1}$ because channel width varied slightly over the period of study, and thus volume per length is the most accurate way to report these data. However, in Table S1 in Supporting Information S1, we provide necessary information to convert the data to $m^3 ha^{-1}$ (the most commonly used metric of wood load) by reporting the average extended channel width over the time period. Most input volume in both the NF and SF came from standing trees and stumps (I_t) or entered the channel from storage by bed or bank erosion (I_s). There was also a significant added volume of unidentified moved pieces (I_m, some of which were likely previously tagged but now unidentifiable) in the NF, particularly in the 2005–2006 interval which included the highest flow during the study on the NF. Throughout the 20-year study, NF losses were dominated by decreases in volume of pieces that were moved, broken, or repositioned in the extended channel (N_m), with our estimated unknown losses (U_g) important in 1998 and unknown gone (L_g) important in 2005–2006 and 2007–2008. In the SF, the net loss in broken or moved pieces (N_m) was generally much smaller than in the NF, and losses to storage (L_s) or unknown gone (L_g) were often as large as changes in moved pieces. A large net change in moved pieces (N_m) in the SF in 2018 reflects a channel change that increased the volume of a large old-growth piece included in the active channel. Normalized losses (volume lost over the interval divided by total volume at the start of the interval) in the two channels were similar, with 2.8% loss in the NF and 2.9% in the SF, averaging across all time intervals.

Wood volume in the NF was higher relative to the SF at the start of the study period and remained higher than the SF throughout the 20-year period (Figures 2c and 2d). The two reaches had similar and stable amounts of old-growth redwood, but the NF had much more volume in older nonredwood pieces (1900–1989 in Figure 2d) as well as in pieces that entered during or shortly after logging (Figure 2c; 1989–1994 and 1995–1996 entry dates), much of which remained in the channel, making up about 26% of the volume in 2018 (Figure 2c). NF total volumes continued to increase through 2004, then stabilized through 2018 with a slight decrease from 2016 to 2018. SF volumes were stable until about 2006 and have been increasing since then, partly because of large old-growth redwood stump inputs in 2014 and 2016 (Figures 2b and 2d). The rate of change between 1998 and 2018 on the SF is ∼2.5 $m^3 km^{-1}$ per year over the 20-year period. Using this average increase, it will take ∼64.5 years from 2018 for the SF volume to reach the volume on the NF in 2018. If additions from old-growth redwood stumps, which are limited in number and nonrenewable, are not included, the average rate of volume increase on the SF is ∼1.4 $m^3 km^{-1}$ per year, with a time scale of ∼112 years from 2018 at this rate for the SF volume to reach the volume on the NF in 2018. Although these estimates are simplified and do not account for future changes in tree stand structure which would affect inputs, nor possible differences in decay rates, these estimates provide a first-order approximation for the time required for SF volumes to reach NF volumes.

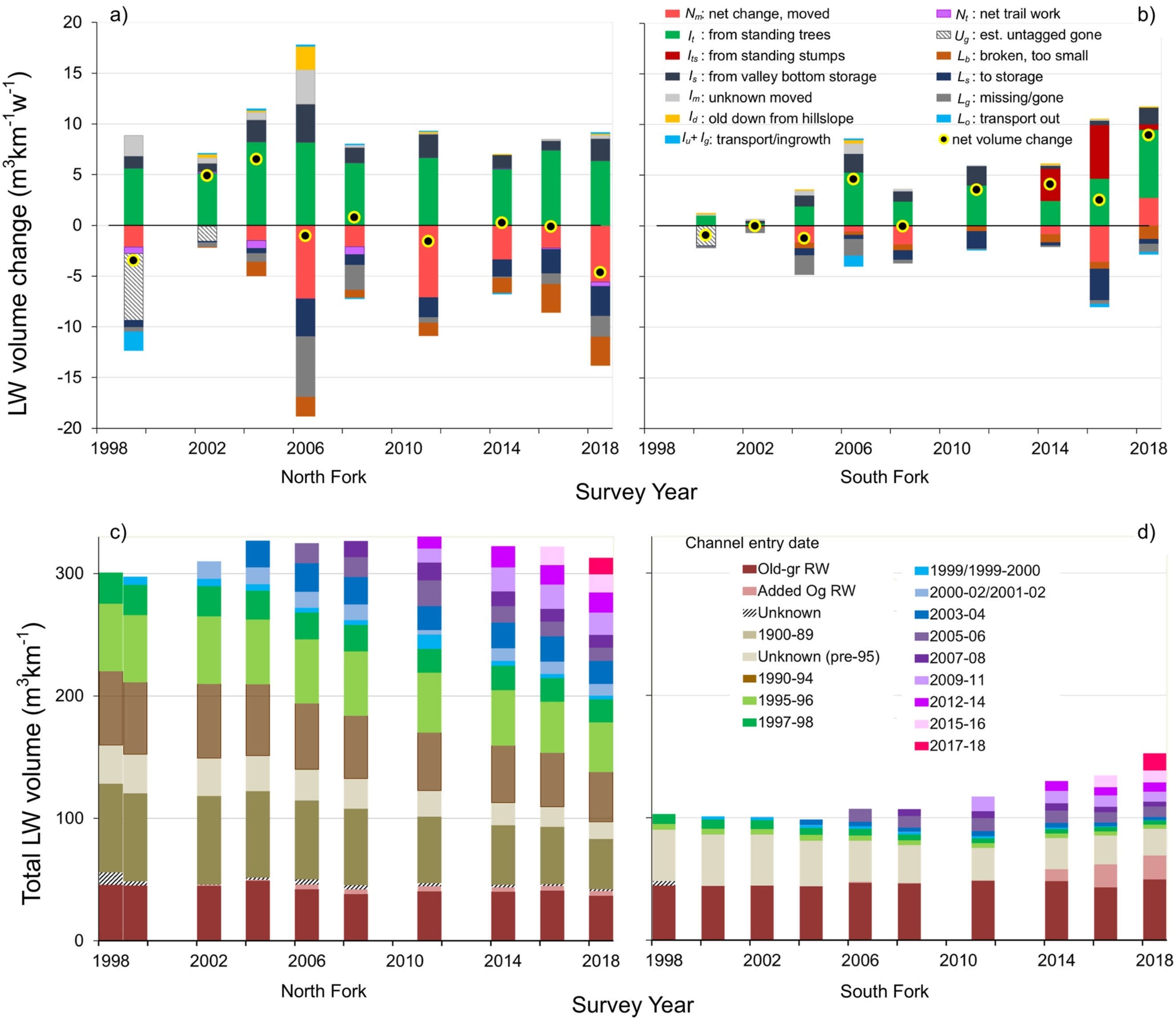

Figure 2. Inputs, losses, and net changes on (a) the North Fork (NF) and (b) the South Fork (SF) from 1998 to 2018. Values are those listed in Table S1 in Supporting Information S1. Fluxes are shown in the ending year of each sampling interval. Total volume over time for (c) the NF and (d) the SF is colored by the down date group (i.e., the time interval during which the pieces entered the channel). *Old-gr RW* are residual old-growth redwood pieces in the channel in 1998; old-growth redwood pieces added later from hillslopes (standing stumps or fallen from banks) are *added OGR*. Because the NF was surveyed in 1999 and the SF in 2000, the 1999/1999–2001 and 2000–2002/2001–2002 down date groups are slightly different time periods in the two channels. Unknown categories are divided into unknown and unknown pre-1995, since for some piece we identified that the piece entered before 1995 but not the exact time interval. Unknown includes estimated volume of untagged pieces (U_g) as well as pieces tagged later of unknown age.

3.2. LW Inputs From Standing Trees

Inputs from standing trees varied between the two reaches. Figure 3 shows counts of inputs from standing trees (I_t) by species and input mechanism into each channel during the study period. The NF had higher total inputs (408 nontrail-work inputs on the NF compared to 244 on the SF between WY 1995 and 2018); 79% of these NF inputs were windthrown or wind-snapped (WTS) whitewoods, which include Douglas-fir, grand fir, hemlock, and unknown nonredwood (Figures 2a and 2c). About 27% of all NF WTS trees entered between WY 1995 and 1998. SF inputs were more varied both by input mechanism and species, with alders, which were not present on the NF, making up 57% of the total (Figures 2b and 2d). SF whitewoods were also primarily WTS, but 42% of SF conifer (whitewoods and redwoods) inputs were redwoods; most of those entered by landslides or bank erosion. Counts by species and input mechanism are listed in Table S2 in Supporting Information S1.

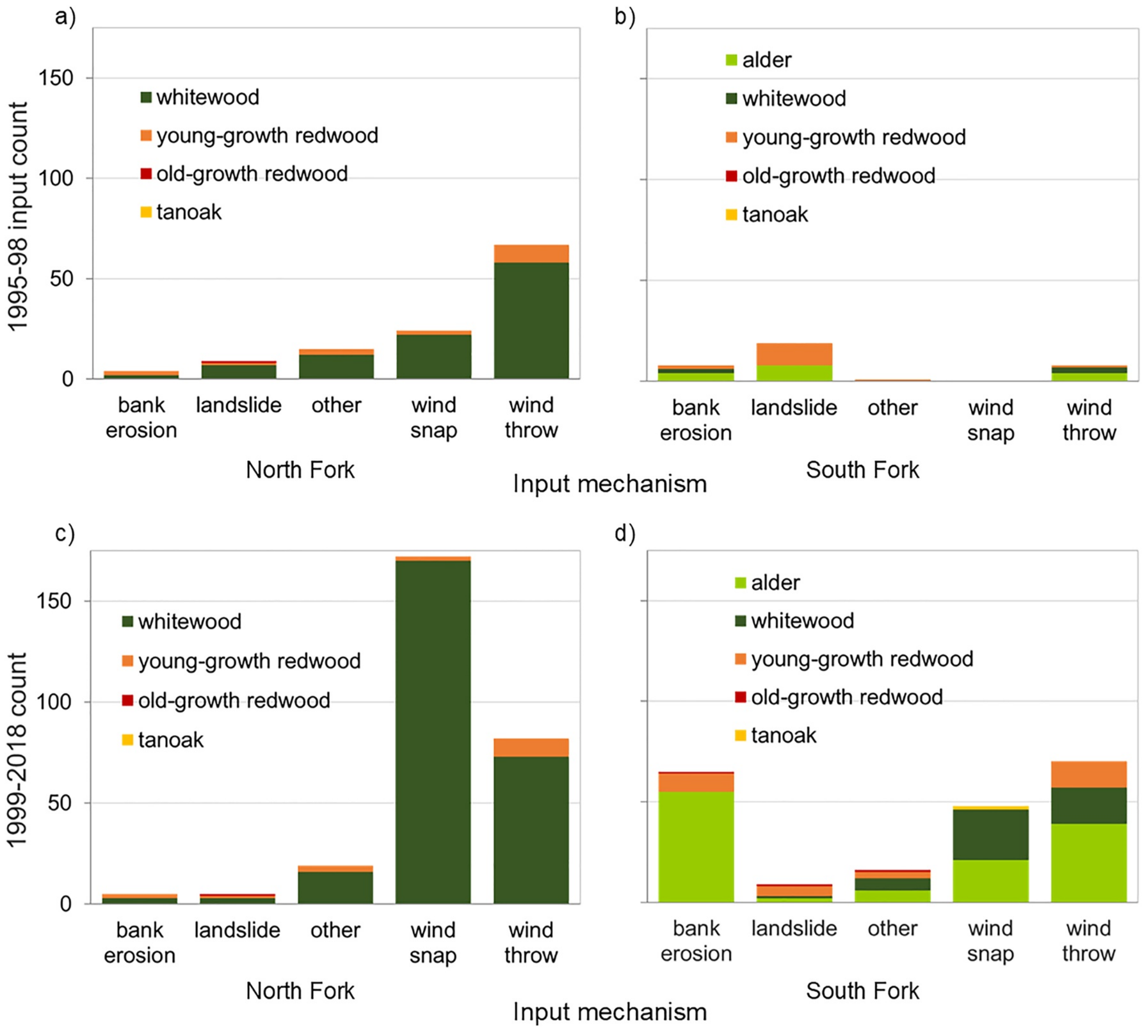

Figure 3. Counts of inputs by species and input mechanism from WY 1995 to 1998 for the North Fork (NF) (a) and South Fork (SF) (b) and from WY 1999 to 2018 for the NF (c) and SF (d). The *other* category includes both trees hit by other trees and new pieces of unknown origin.

NF inputs came from further from the channel bank than SF inputs, both because SF inputs were dominated by near-channel inputs from bank erosion and landslides and because NF WTS inputs came from greater distances than SF WTS inputs. Figure 4 shows cumulative source distance distributions by input mechanism for NF and SF hillslope inputs (I_l) during the study period. Landslide and bank erosion pieces originated from similar distances on the NF and SF. Total inputs from landslides were low (12 pieces from seven events on the NF, 25 pieces from eight events on the SF), so these data may not represent long-term patterns depending on the frequency of landslides. Much of the wood volume inputs from landslides on the SF originated from near the bank (Figure 4d) due to inputs from large channel-adjacent old-growth stumps (Figure 2d). The SF also had high numbers of bank-eroded inputs (Figure 3d), making up 20% of the inputs by volume on the SF. This high volume of near-bank inputs meant that total SF input volume was dominated by near-bank pieces, with half of the input volume originating 3 m or less from the bank. By contrast, only 12% of NF total input volume came from 3 or less from the bank. WTS pieces also came from closer to the bank on the SF compared to the NF. In the SF, 90% of WTS pieces came from 17 m or less from the bank, while 90% of WTS pieces on the NF came from 32 m or less. Note that these data are for tagged pieces meeting our criteria of a minimum diameter of 0.2 m and a minimum length of 2 m within the extended channel. If we had included pieces meeting the smaller size criteria used in many LW studies, maximum distances would likely be longer as small diameter pieces from tops of trees further from the bank would have been included.

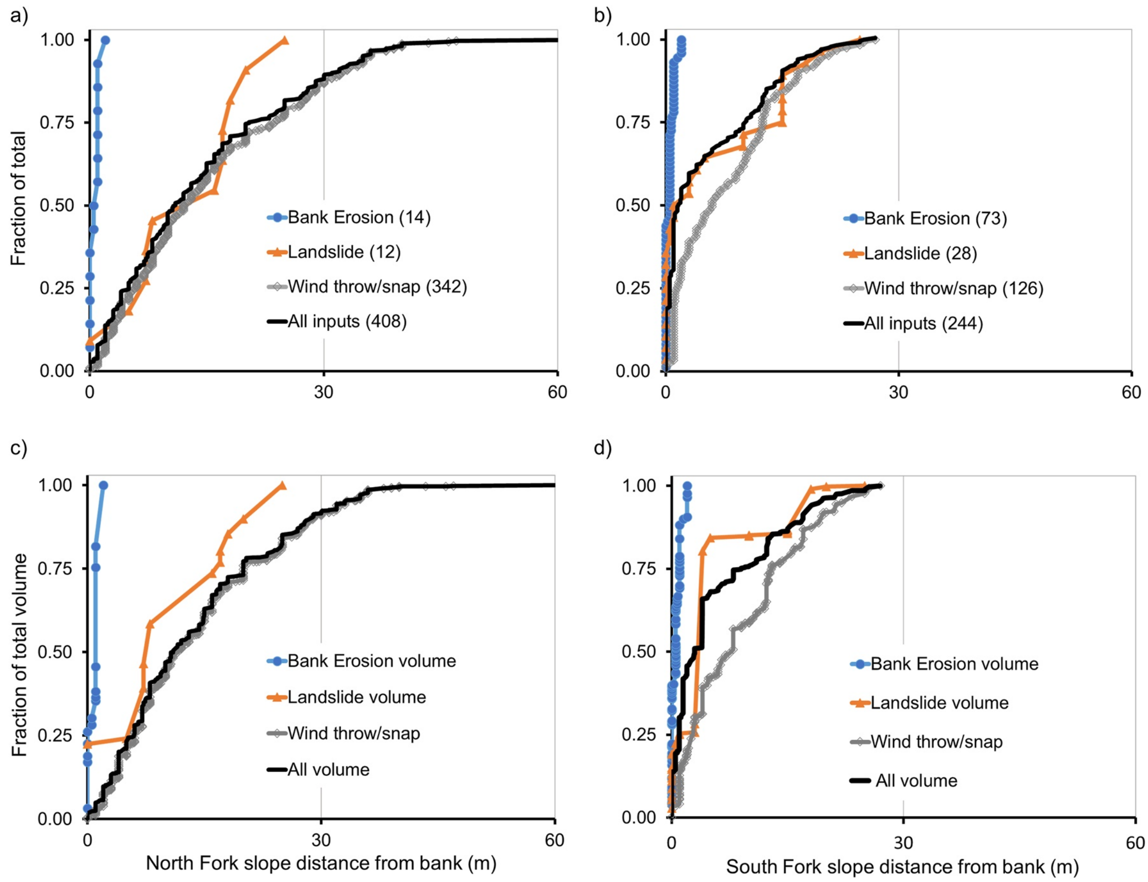

Figure 4. Source distance cumulative distribution of inputs by input mechanism. North Fork (NF) (a) and South Fork (SF) (b) counts are of individual trees contributing at least one taggable piece (>2 m within the extended channel and 0.2 m diameter) to the channels during the study period. Total volume inputs from NF (c) and SF (d) are also shown. Pieces that entered by being hit by other trees are not plotted separately but are included in all inputs; those pieces typically originated close to the channel.

Results from input rate modeling by subreach are in Table 2, which shows the predictors included in the top model for each response variable, along with importance values (sum of the Akaike weights from all possible models) for the predictors included in the top model. Text S3 in Supporting Information S1 describes the models in more detail, and Table S3 in Supporting Information S1 lists all predictors in models with AICc values less than 2 units different than the top model.

Modeling results indicated that weather factors, particularly the number of high wind events that coincided with high flows, were clearly important in both the NF and SF. This was the case when modeling all years and only post-1998 inputs. Steeper slopes also seem to be associated with higher input rates for the NF across all years and in the SF after 1998. However, other factors were quite different between the NF and the SF and to a lesser degree between models including all years and those including only inputs after 1998. The extremely high wind in December 1995 (the highest recorded during the study) was strongly associated with high inputs in the NF, but not in the SF. SF inputs consistently increased with time (*Yrs95*), but there was no strong association between inputs and time (*Yrs95*) on the NF. Distance from the nearest clearcut margin in the NF was important when considering inputs after 1998 but not across all years (Figure 5a).

As Figure 5a shows, NF WTS inputs, which comprised most of the total NF inputs, were higher in subreaches closer to clearcuts from 1995 to 1998 but lower after 1998 in those same subreaches. Subreaches close to clearcut margins (Figure 5a) lost many potential input trees during and just after logging (1995–1998), likely reducing supply in the future. The subreach at 188 m from a clearcut margin included a tributary junction where high winds in 1995 caused high windthrow into the tributary as opposed to the NF. Although not counted as inputs to the NF, the reduction in adjacent supply likely affected the input rates in that NF subreach. For the post-1998

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Table 2
Generalized Linear Mixed Model Results for the Models With the Lowest AICc of All Possible One-Factor to Three-Factor Models (Combinations of One to Three Predictors) for the North Fork and the South Fork for All Years and Post-1998 Only

Response	Time period	Predictor	*p*-Value	Coefficient	Importance
NF inputs	All years *n = 408*	*WM* (maximum windspeed offshore, m/s)	*<0.0001*	0.09	99%
		WWS (wet winter storm, number per winter)	*0.0014*	0.34	85%
		PctSteep (percent of source area with slope >35%)	0.0772	0.95	25%
	Post-1998 *n = 289*	*WWS* (wet winter storm, number per winter)	*<0.0001*	0.42	99%
		DistMar (mean distance to the nearest clearcut margin, m)	*0.0164*	0.003	46%
SF inputs	All years *n = 244*	*Yrs95* (number of years since 1995)	*0.0007*	0.04	95%
		WWS (wet winter storm, number per winter)	*0.0258*	0.30	70%
		PctRWW (percent of total nonclearcut area classed as redwood-dominated)	0.1115	−0.005	28%
	Post-1998 *n = 208*	*Yrs95* (number of years since 1995)	*0.0032*	0.04	93%
		WWS (wet winter storm, number per winter)	*0.0306*	0.30	60%
		PctSteep (percent of source area with slope >35%)	*0.0445*	0.01	37%

Note. Predictor variables significant at alpha = 0.05 are italicized. Importance values are the sum of the Akaike weights from all possible models.

model, inputs increased slightly with increasing distance from a clearcut margin, potentially highlighting that these subreaches further from clearcuts that did not experience high inputs postlogging had more potential inputs remaining for recruitment.

SF input rates were lower than NF rates, across all years and post-1998 (Figure 3). Most SF inputs were alders (Figure 3 and Table S2 in Supporting Information S1), and the increase in inputs over time (*Yrs95*) in the SF input models likely reflects increased alder inputs as alders that sprouted after the 1970s logging grew big enough to be counted when they fell and entered the channel. SF WTS inputs, which were the majority of SF inputs, were lower than NF, and much lower than NF 1995–1998 windstorm-affected inputs (Figures 5a and 5b). Figure 5b shows post-1998 WTS SF conifer inputs and all NF inputs (all NF inputs were conifers except two tanoaks, included

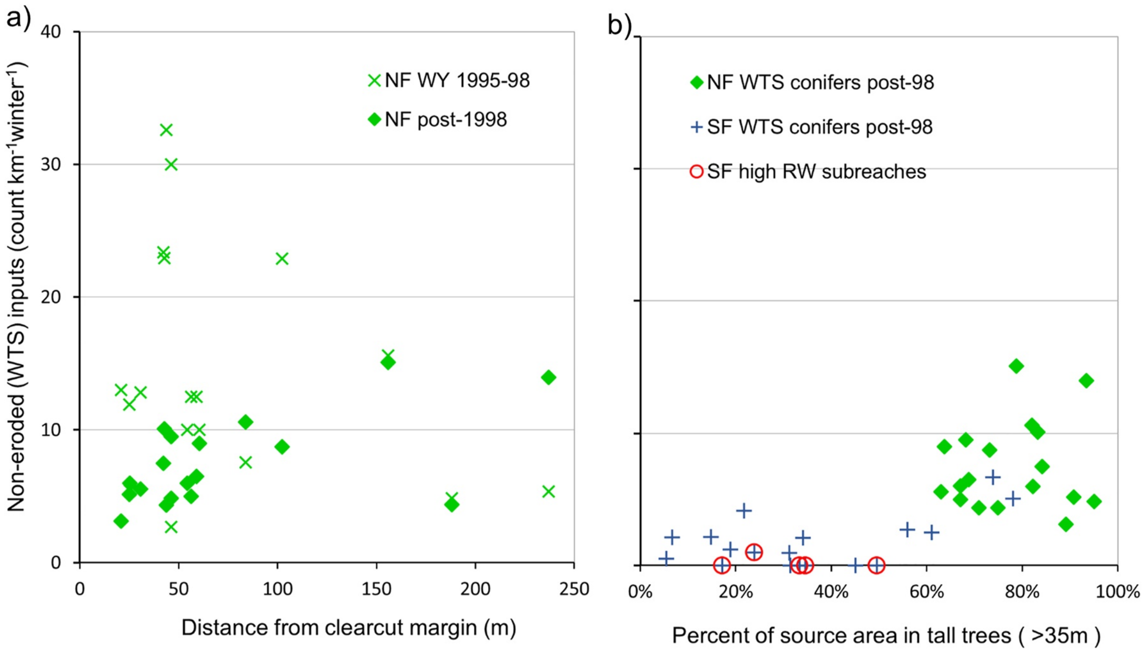

Figure 5. Windthrown or wind-snapped (WTS) input rates; (a) North Fork (NF) inputs by subreach versus distance from the nearest clearcut margin for WY 1995–1998 and WY 1999–2018, and (b) WTS conifer inputs on the NF and South Fork (SF) versus percent of stand in tall trees >35 m in height. The high redwood subreaches in (b) had input areas classified as >50% redwood in both 1998 and 2007.

with conifers for simplicity), against the percent of stand in tall trees >35 m in height. The SF subreaches that were least impacted by the 1968–1973 logging, with tall tree coverage in the same range as NF subreaches, had WTS conifer input rates comparable to those in the NF.

3.3. Wood Mobility

On the NF, 470 of 1,303 (36.1%) unique pieces moved at least once, while only 141 of 476 (29.6%) unique pieces moved at least once on the SF. Mapping pieces every ∼2 years over a 20-year period on the SF and NF resulted in 8,452 displacement length observations. A large proportion (88.2%) of these observations were zero, indicating no movement. The odds of entrainment (observed movement) decreased as the piece size increased (diameter and piece length/channel width), as reach slope increased, and if a piece was partially located on a vegetated bar or had a rootwad (Table 3 and Figure 6). Rootwads were present on 30.8% of displacement length observations, and pieces with rootwads had higher piece length to channel width ratios compared to pieces without rootwads (Figure S2 in Supporting Information S1). In addition, relative to the in-channel position, pieces in other positions (partially in the channel, spanning the channel, on the bank, or high spanning over the channel) were less likely to move (Figure 6). The odds of entrainment increased slightly with the occurrence of storm discharge events (PkSD, described in Table 1, >0.61 m at the weirs), and increased more significantly with the frequency of the higher 1-year recurrence interval flows (PkAy, described in Table 1, stage >0.88 m at the NF weir and >0.91 m at the SF weir). In addition, pieces that were buried were less likely to move (Figure 6). As the density of pieces within a subreach increased, the odds of movement increased (Table 3).

Once pieces became entrained, smaller pieces (i.e., smaller diameters and smaller piece length/channel width ratios) moved farther (Table 3 and Figure 7). In addition, if pieces were located in a subreach with lower piece density per channel length, pieces moved farther. Farther displacement lengths were associated with pieces more parallel to the channel angle (0°) compared to perpendicular (90°), but the effect was quite small with the coefficient close to zero (Table 3). Piece characteristics such as whether the piece had a rootwad, was located on a vegetated bar, or was partially buried and the piece position in the channel were not strongly associated with displacement length. Similar to controls on entrainment, both the number of storm events and the number of 1 year or greater recurrence interval flows were significant predictors of displacement length, but the number of 1-year recurrence or greater interval flows had a stronger effect, as demonstrated by the higher β coefficient in the model (Table 3 and Figure 7).

As shown in the cumulative distribution in Figure 8, pieces tended to move farther on the SF compared to the NF. Although species was not included in the statistical models because species is highly correlated with piece diameter (Figure S3 in Supporting Information S1), different species moved more frequently than others, with the general pattern that species with smaller diameters had more frequent observations of some movement (Figure 8). Pieces in jams had a slightly higher proportion of observations with movement (Figure 8), and pieces in jams were generally slightly smaller than pieces not within jams (Figure S4 in Supporting Information S1) (data from 2008 onward). Additional statistics on subreach geomorphology and summary statistics for the movement observations are included in Tables S4–S7 and Figure S5 in Supporting Information S1.

4. Discussion

4.1. Controls on Long-Term Wood Loads and Inputs

Our results indicate that the different management histories of the NF and SF continue to affect LW volumes decades after logging, with the SF having a significantly lower volume of LW (Figure 2). Figure 9 conceptually summarizes the history of LW volumes in the NF and SF, including variations in volume over time, generalized species composition, and major input and removal events along with dominant input species during the study period (1998–2018). Channel wood removal and intense partial cutting adjacent to the channel during the SF logging in the early 1970s was still affecting channel volumes in 2018, ∼50 years after the activity took place. Residual old-growth redwood volume in the two channels was similar and stable through the course of the study (Figures 2c and 2d), but the NF had more LW volume that was not old-growth redwood throughout the 20-year period. Some of the NF volume came from pieces that entered during and immediately after logging in the late 1980s and early 1990s, some during extreme wind events (almost 40% in 1998, 26% by 2018). Those inputs were higher near the forest openings created by clearcuts during logging (Figure 5a), exposing trees within the riparian

Table 3
Model Summary of the Logistic Regression to Assess Controls on Movement Versus No Movement (Entrainment) and of the Mixed Effects Linear Regression With Multiple Covariates to Assess Controls on the Displacement Length of Pieces That Moved

Dependent variable	Predictor variable	*p*-Value [exp(coefficient *β*)][a]	Odds of movement decrease (−) or increase (+) by[b]
Movement versus no movement	*Diameter (m)*	<0.001 [0.13]	−0.86%
	Angle to channel (°)	0.715 [1.00]	
	Piece length/channel width (m/m)	<0.001 [0.68]	−0.32%
	Slope (%)	<0.001 [0.67]	−0.33%
	Piece density of subreach (pieces per m)	0.031 [2.41]	+141%
	PkSD (number per winter)	<0.001 [1.06]	+6%
	PkAy (number per winter)	<0.001 [1.33]	+33%
	rootwad_Yes (reference group: rootwad_No)	0.007 [0.69]	−31%
	position_partiallyin (reference group: inchannel)	<0.001 [0.34]	−66%
	position_span (reference group: inchannel)	<0.001 [0.28]	−72%
	position_bank (reference group: inchannel)	<0.001 [0.15]	−85%
	position_highspan (reference group: inchannel)	<0.001 [0.12]	−88%
	hinged_Yes (reference group: hinged_No)	0.065 [0.60]	
	vbar_Yes (reference group: vbar_No)	<0.001 [0.36]	−64%
	buried_Yes (reference group: buried_No)	<0.001 [0.18]	−82%
Dependent variable	Predictor variable	*p*-Value [coefficient *β*][a]	
Displacement length for observations > 0	*Diameter (m)*	0.006 [−1.35]	
	Angle to channel (°)	<0.001 [−0.01]	
	Piece length/channel width (m/m)	<0.001 [−0.39]	
	Slope (%)	0.602 [−0.07]	
	piece density of subreach (pieces per m)	<0.001 [−3.27]	
	PkSD (number per winter)	0.002 [0.06]	
	PkAy (number per winter)	<0.001 [0.48]	
	rootwad_Yes (reference group: rootwad_No)	0.486 [0.15]	
	position_partiallyin (reference group: inchannel)	0.059 [−0.27]	
	position_span (reference group: inchannel)	0.133 [−0.46]	
	position_bank (reference group: inchannel)	0.073 [−0.62]	
	position_highspan (reference group: inchannel)	0.494 [−0.34]	
	hinged_Yes (reference group: hinged_No)	0.314 [−0.44]	
	vbar_Yes (reference group: vbar_No)	0.616 [−0.16]	
	buried_Yes (reference group: buried_No)	0.321 [−0.38]	

Note. Predictor variables significant at alpha = 0.05 are italicized.
[a]For categorical variables, *β* coefficient is an adjustment to the model intercept relative to the reference group; for numeric variables, *β* coefficient is an adjustment to the slope. [b]This column indicates the increase or decrease in the odds of movement with a one unit increase in the predictor variable.

buffer strips and nearby stands to windstorms. Although it is likely that these windstorms would have caused some LW inputs even without edge effects, it is interesting that there was no measured effect of the windstorms in the SF, where there were fewer tall trees (Figure 5c), smaller openings, and edges had had many years from the time of logging to stabilize. In British Columbia, Canada, logged reaches with a 10-m-wide buffer strip received more pieces due to windthrow in multiple sites compared to unlogged control reaches (Bahuguna et al., 2010). However, even accounting for the ~26% of the NF LW volume in 2018 that originally entered following logging in the late 1980s and early 1990s, the NF volumes are still significantly higher than SF volumes, reflecting both instream LW removal and reduced inputs on the SF. Our results are similar to other studies, which have

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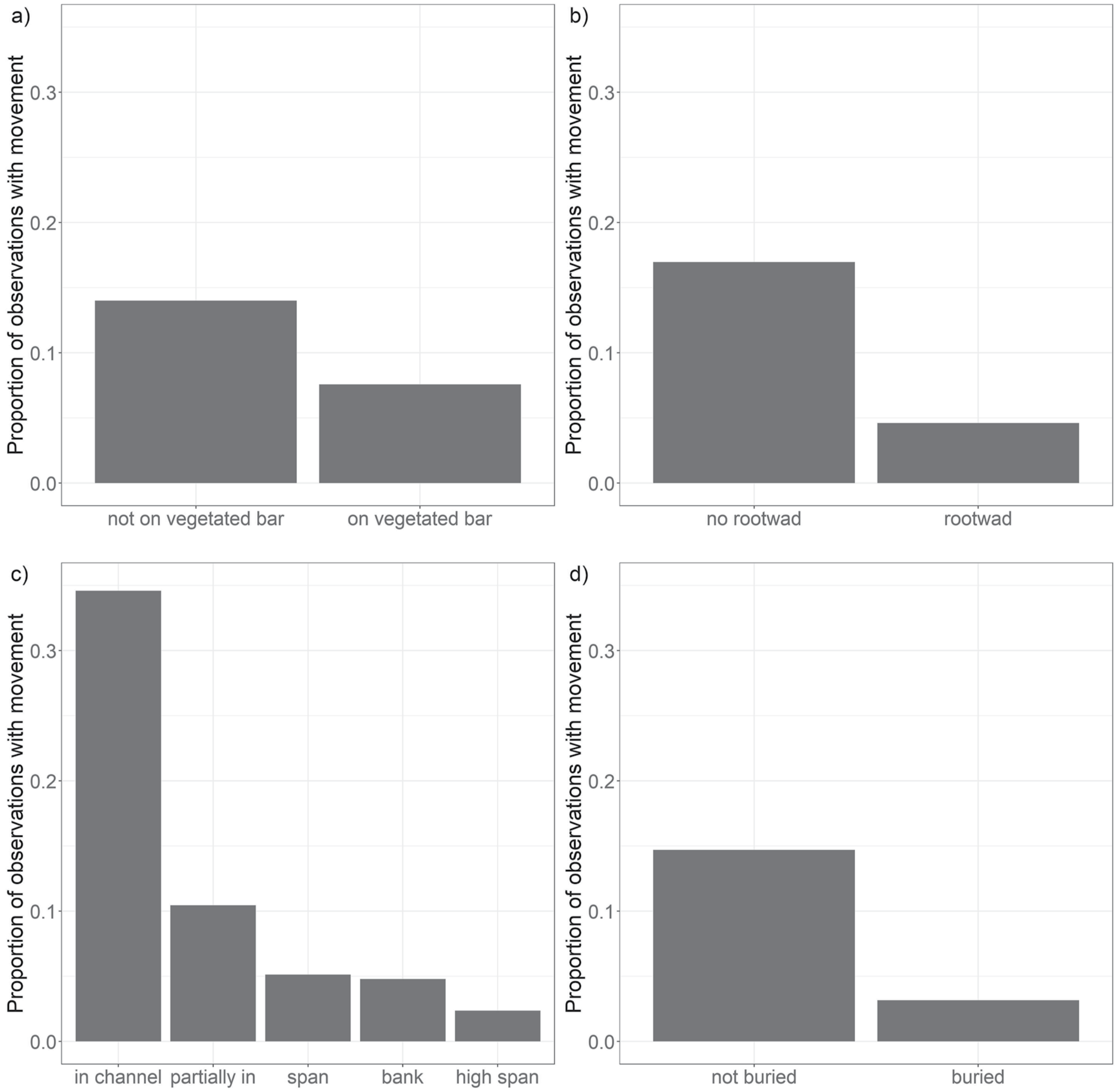

Figure 6. The proportion of observations with movement (entrainment) for pieces not located or at least partially located on a vegetated bar (a), with or without a rootwad (b), position in the channel (c), and not buried or buried (d).

demonstrated that logging results in lower instream LW volumes (Benda & Bigelow, 2014; Livers et al., 2018; Reid & Hassan, 2020; Scott & Wohl, 2018). In our study, we find that near-channel logging with instream LW removal results in lower LW volumes compared to logging with buffer strips.

Reduced inputs of LW pieces on the SF show the effect of heavy cutting, without buffer strips, in channel-adjacent stands in the SF in the 1970s, which reduced the number of tall older trees available to enter that channel (Figures 3 and 5b). SF windthrown and wind-snapped (WTS) conifer input rates were close to NF input rates in subreaches where the percent of the canopy >35 m tall was closer to canopy values in the NF, which were generally much higher than in the SF (Figure 5b). The higher NF input values reflected the presence of taller, older trees retained in buffer strips and in stands that had not been cut since initial wide-spread logging in the late nineteenth century. Older tree stands resulting in greater volumes recruited into channels has also been found elsewhere (Warren et al., 2009). Near-channel roadbuilding in the SF also reduced the number of trees in near-channel stands and may have contributed to shorter inputs distances in the SF (Figure 4). Shorter source distances in the SF are consistent with Benda and Bigelow (2014), who found that in managed streams in northern California, the distance over which wood is recruited was shorter in managed and logged watersheds compared to

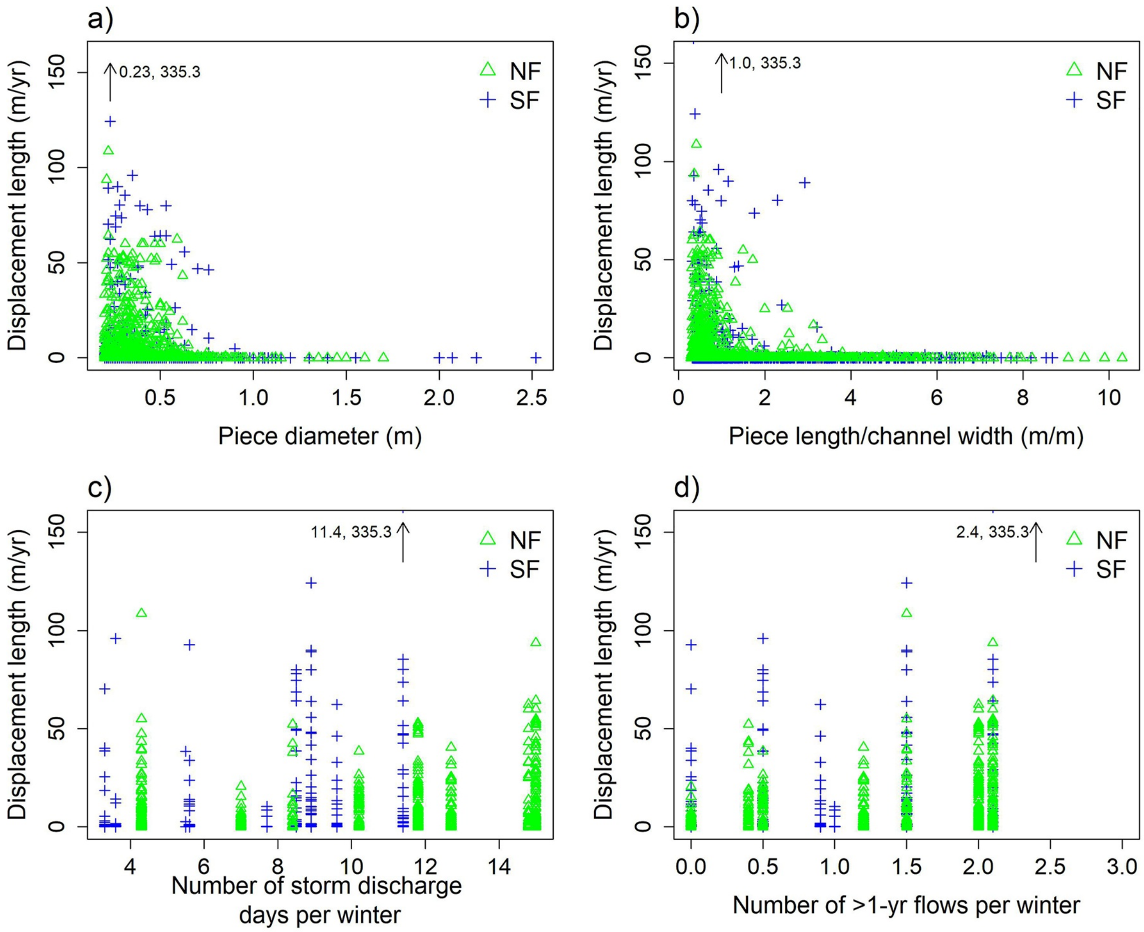

Figure 7. Displacement length observations on the North Fork (NF) and South Fork (SF) versus (a) piece diameter, (b) piece length/channel width, (c) number of days discharge exceeded storm discharge per winter for the interval, and (d) number of >1-year recurrence interval flows per winter for the interval. On all plots, the arrow denotes an observation not shown, with the datapoint value listed.

unmanaged watersheds. In our case, the watershed with intensively managed riparian stands (the SF) has a shorter source distance compared to the watershed with less intensive near-stream management (the NF).

Differences in input rates and volumes between the NF and SF, however, are not entirely a result of different management, and point to the effects of riparian species composition and other factors on LW inputs. Alder presence and abundance along the SF channel, which occupied potential growing space for larger and longer-lasting conifers but also contributed to channel wood, were partly a management effect (alders increased following logging in that channel), but also reflect a basic difference between the channels. The SF also had scattered larger, older alders that clearly predated the logging, while the NF has never had a significant alder presence. Postlogging alder inputs into the SF made up much of that channel's high numbers and volume of bank erosion inputs (Figure 4 and Table S2 in Supporting Information S1). The SF also had a higher proportion of redwoods (although redwoods were the dominant species in both forks), which probably contributed to lower overall input rates there. Redwood input rates were much lower than whitewood inputs in both channels (Figures 3 and 5b). Redwoods, with their long natural lifespans (Fritz, 1957), are less likely than other species to die and break off into the channel (wind-snapped trees were generally dead before breaking). Young redwoods are also resistant to windthrow (Burns & Honkala, 1990). As Figure 5b shows, WTS conifer input rates from strongly redwood-dominated stands in the SF were quite low. An additional reason that standing tree input rates were lower on the SF may be because SF hillslopes were less steep (the average percent of area >35% slope was 53% in the NF, 31% in the SF), and steeper slopes are associated with higher input rates (Table 2).

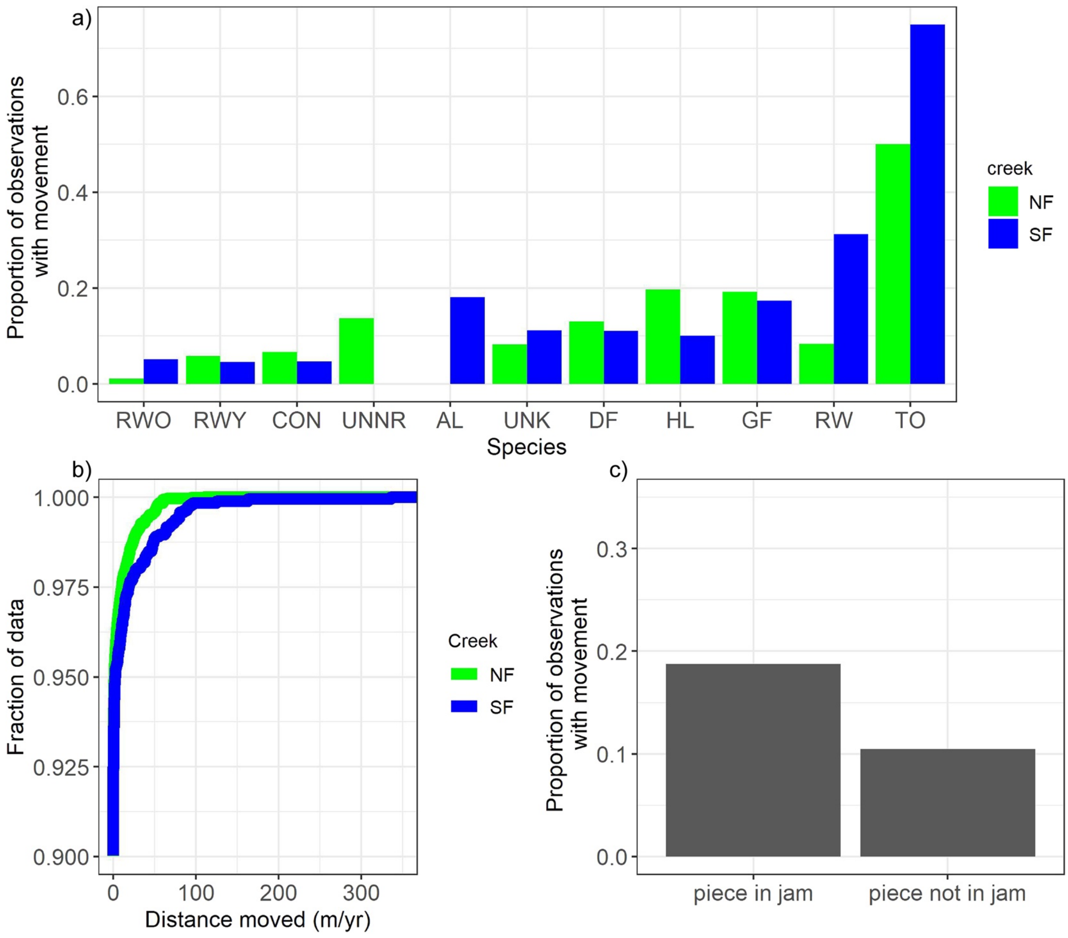

Figure 8. Proportion of displacement length observations by species (a), the cumulative distribution of displacement length on the North Fork (NF) and South Fork (SF) (b), and the proportion of displacement length observations by whether or not a piece is in a jam. Species codes are red alder (AL), unknown conifer species (CON), Douglas-fir (DF), unknown nonredwood (UNNR), grand fir (GF), western hemlock (HL), coast redwood of unknown age (RW), old-growth redwood (RWO), second-growth or third-growth redwood (RWY), tanoak (TO), and unknown (UNK).

Stand composition and structure interact with windstorms and geomorphic processes to influence patterns of inputs. Very high winds in 1995 affected inputs in the NF, but inputs into the SF in the same period were low, probably due to differences in stand structure and composition. Wet windstorms were an important predictor for inputs into both the NF and SF, despite different dominant input mechanisms. In a much larger watershed in the Czech Republic (13,419 km^2), bankfull discharge and other high flow events best explained the variability in wood input rates compared to wind events (Máčka et al., 2020).

Total losses over the study period were lower on the SF compared to the NF (Figure 2). Much of that difference can be explained by the lower wood volume in the SF channel, as the NF and SF had similar losses when normalized by the total volume at the start of the time interval. In addition, there is a larger proportion of the SF volume that is old-growth redwood (Figure 2). This may have resulted in lower volume losses in the SF, since old-growth redwood piece size was generally larger than other species (Figure S3 in Supporting Information S1) and piece size strongly influenced mobility. In addition, most volume losses were due to attrition, breakage, and net change in volume of moved pieces (Figure 2), and redwoods' high resistance to decay (Sawyer et al., 2000) would make those pieces less subject to those loss mechanisms. However, more work is needed to constrain the impacts of species differences on instream volume changes, particularly as it relates to decay, attrition, and breakage.

During the 20-year course of the study, NF volumes remained quite high, with inputs roughly equaling outputs (Figure 2). These volumes may not remain stable if loss rates change over time due to changes in decay rates or if input rates change in response to changes in stand structure and composition. For example, riparian stands are

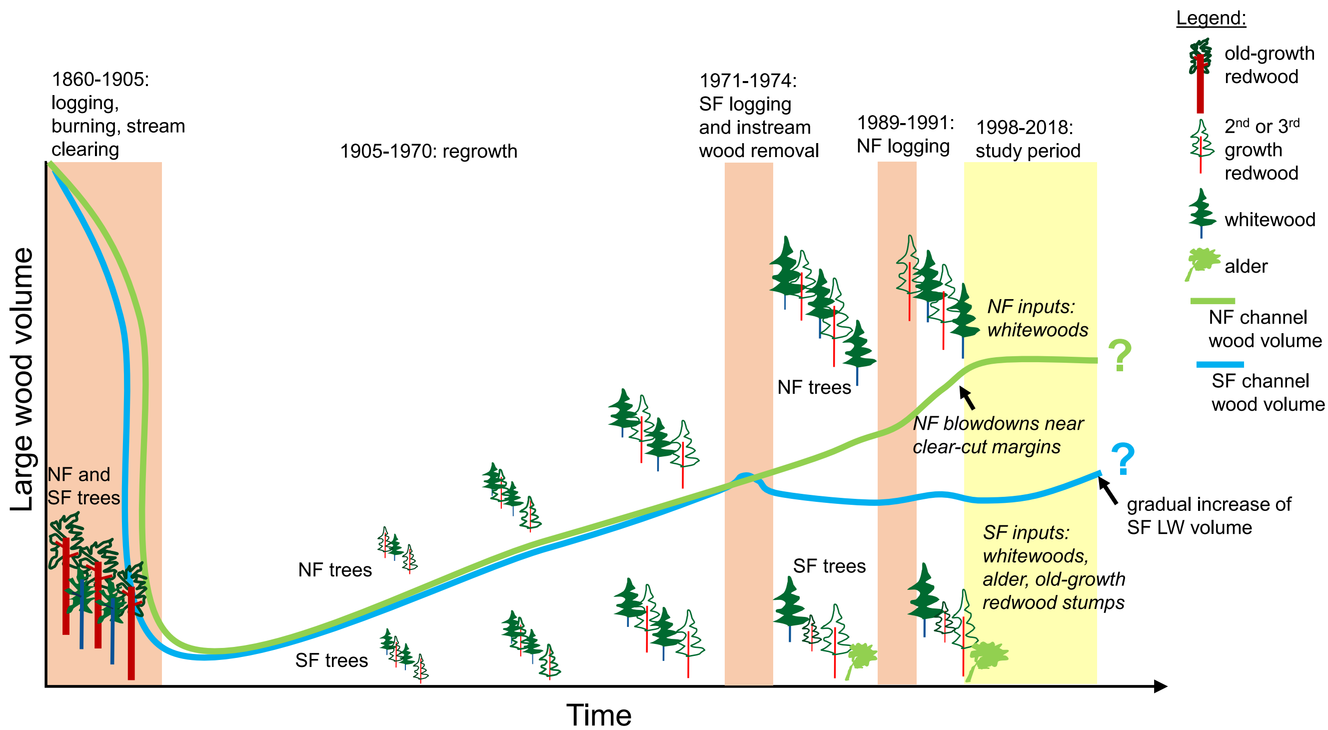

Figure 9. Conceptual figure of the North Fork (NF) and South Fork (SF) over time, demonstrating large wood (LW) volumes, riparian species composition, major input and removal events, and dominant species inputs during the study period (1998–2018).

still dominated by trees of a single age class, and changes might be expected as the stand becomes more multiaged and more dominated by long-lived redwoods. Although the total LW volume on the NF during the study period was affected by logging-related inputs, the fluctuations in volume after those inputs were minimal. In contrast, the LW volume on the SF increased over time.

The volume on the SF over the 20-year period was low between 1998 and 2004, and then began to increase through 2018. Thus, it is possible that the minimum LW volume following logging and LW removal on the SF occurred ∼30 years after the 1970s harvest. Using the average rate of increase for the SF volume and comparing it to the 2018 NF volume, the total time for the SF to reach NF levels from the early 1970s when the SF was logged would be ∼112 years, or 160 years if the added volume from old-growth stumps (Figure 2) is excluded from the increase rate calculation. Reid and Hassan (2020) modeled a wood budget for a watershed in British Columbia, Canada that was previously logged. They estimated that the time to LW minimum would potentially occur 50–80 years postharvest, and that it may take >150 years to return to preharvest levels, with variations in that time scale dependent on logging scenarios (Reid & Hassan, 2020). Our time scale estimates of how long it may take the SF to reach NF volumes assume that the SF volume will continue to increase at a rate comparable to the existing rate of increase. Input and loss patterns in both channels are likely to change in the long term as the stands become more like old-growth redwood stands, which were the original stands in this area prior to late nineteenth century logging. It will likely take several hundreds of years of careful protection and management to develop old-growth-like forests along these channels. Such forests are necessary for providing pieces equivalent to the very large and long-lasting pieces found in channels adjacent to old-growth stands (Keller & MacDonald, 1983). Models of tree growth and mortality by species, combined with calculations of how long pieces survive in the channel, would give us better estimates of the long-term wood budget. However, it is interesting to find a similar magnitude of time scales of our first-order approximations to other studies in a similar biome (Reid & Hassan, 2020), and estimates for the time scales for recovery of instream wood loads after logging are similar but slightly longer in the Rocky Mountains (e.g., ∼200 years or more; Livers et al., 2018) and southeast Australia (e.g., 255 years; Stout et al., 2018).

It is important to note that the definition of LW used in our analyses includes pieces >2 m in length and >0.2 m in diameter, which is larger than the common definition of LW used in most studies (>1 m in length and >0.1 m in diameter). Thus, the changes in volume and inputs over time do not reflect the differences that may have occurred in smaller LW size classes, which may bias our results. Further work that incorporates multiple size classes of LW could shed light on whether changes in the largest size classes are similar to and reflect wood dynamics across a range of sizes. In addition, although the data set presented here is detailed and extensive, differences in measurement techniques over the long timespan of the study (20 years) may have influenced the precision of some of the measurements.

4.2. Controls on LW Mobility

On the NF and SF of Caspar Creek, LW pieces moved infrequently and displacement lengths tended to be small. As our results indicated, piece size relative to the channel width in the SF and NF strongly influenced entrainment and displacement length, and piece sizes were large compared to channel width on Caspar Creek. In other regions where piece size is generally smaller, studies report longer displacement lengths (e.g., Dixon & Sear, 2014; Iroumé et al., 2018; Wohl & Goode, 2008). As noted above, our definition of LW is larger (>2 m in length, >0.2m in diameter) than the common definition used in other studies; we likely would have observed more frequent transport and greater displacement length if the tracked pieces used to the most common definition of LW. Multiple studies have found that piece dimensions relative to channel size influence wood mobility (Braudrick & Grant, 2001; Dixon & Sear, 2014; Iroumé et al., 2018; Wohl & Goode, 2008). Although our results are most relevant to streams where piece size is large relative to channel size, our data set can be viewed as strong confirmation of the results of other studies conducted over shorter time scales, since our data set includes >8,000 observations over 20 years. Another geomorphic characteristic that was associated with entrainment was channel slope, with subreaches with higher slopes having pieces that are less likely to move. This may be related to channel width, since steeper subreaches were associated with smaller channel widths (Figure S5 in Supporting Information S1).

Our combined analysis of both entrainment and displacement length point to the complexities of LW mobility. Categorical piece characteristics such as whether a piece has a rootwad, is located on a vegetated bar, is buried or partially buried, and if a piece is in the channel as opposed to positions less accessible to channel flow (e.g., spanning), strongly influenced whether a piece becomes entrained, as demonstrated by the results of the logistic regression for movement or no movement (Table 3 and Figure 6). However, the results of the linear regression model of displacement lengths indicate that these categorical piece characteristics (e.g., presence of rootwads, position) were not as strongly associated with displacement lengths compared to piece size (Table 3, Figures 6 and 7). Thus, many piece characteristics influenced LW entrainment (piece size and categorical characteristics), but piece size was more important than position or morphology when assessing how far a piece is transported. This finding is in contrast to other studies that found that pieces without rootwads traveled farther within streams (Iroumé et al., 2018; Ruiz-Villanueva et al., 2020). However, pieces without rootwads tended to have smaller piece length relative to channel width (Figure S2 in Supporting Information S1). Thus, rootwad presence or absence likely influenced displacement length through associations with piece size. The interactions between factors that influence both entrainment and displacement length are complex, and further work is needed to isolate the effect of individual factors.

Storm discharges that occur multiple times per year and higher-magnitude 1-year recurrence interval flows were associated with entrainment and greater displacement lengths, although the higher 1-year flows had stronger effects. These results support previous assertions that lower-magnitude floods influence wood mobility (Máčka et al., 2020), although high flows are likely more effective (Kramer et al., 2017; Schenk et al., 2018; Senter et al., 2017). Our results point to the potential importance of high magnitude floods or debris flows on wood transport. The proportion of pieces that moved was slightly higher for pieces in jams, which is in contrast to other streams, in which increased LW mobility has been associated with pieces not located in jams (Galia et al., 2019). In Caspar Creek, this may be because pieces that were trapped in jams were already mobile (i.e., they had to be mobilized to accumulate in a jam) and had smaller piece lengths relative to channel widths (Figure S4 in Supporting Information S1). Jams have been shown to be dynamic, both losing and gaining pieces (Dixon & Sear, 2014; Wohl & Goode, 2008). In addition, our data set contains information on jams from 2008 to 2018, and thus we were unable to assess the influence of jams over the entire study period. Our definition of jams, as three of more pieces in contact that demonstrated the ability to trap additional pieces, is slightly different than many definitions of jams in other studies (i.e., three pieces in contact only), which may have influenced our analyses.

The higher proportion of observations with at least some movement on the NF compared to the SF likely does not result from differences in piece dimensions between the creeks, since piece dimensions are not markedly different (Table S8 in Supporting Information S1). One possible explanation for this slight difference is that the NF has higher input rates (Figures 3 and 5). When a piece is delivered into the channel, that piece may not be stable relative to the channel and flow conditions, and thus pieces are more frequently moved on the NF due to the increased input rates of new pieces. This is supported by the increased odds of movement in subreaches with a higher density of pieces (Table 2). A higher density of pieces in the channel in the subreach partially reflects input rates, and NF subreaches have a higher density of pieces. However, piece density of the subreaches had an inverse relationship to displacement length, indicating that pieces in high density subreaches moved shorter distances due to more piece-to-piece interactions. The lower-density and lower volume SF also tended to have longer displacements lengths (Figure 8). In the Colorado Front Range, streams in old-growth forests with larger LW loads compared to streams in younger forests had smaller downstream distances between jams, indicating that higher LW loads help trap LW (Beckman & Wohl, 2014). Our results imply that when managing streams to increase LW loads, it may be important to ensure a minimum LW load to reduce LW displacement lengths and thus export.

5. Conclusions

Our results indicate that logging has long-term effects on instream LW loads, at least partly by impacting LW recruitment from standing trees. Tree species interacts with weather and geomorphic processes to influence standing tree inputs into streams. In addition, pieces are relatively stable in headwater streams in redwood regions, but the dynamics of both entrainment and displacement length can be investigated with long-term data sets incorporating piece characteristics, discharge records, and geomorphic characteristics of streams. The unique data sets from Caspar Creek facilitate an increased understanding of LW dynamics, with implications for management of LW and associated habitat. Future work will involve greater exploration of the dynamics of attrition and breakage of wood in Caspar Creek, as well as developing a wood budget model that can be validated using the long-term, detailed, and frequently measured LW data set.

Data Availability Statement

Data in the paper are available online through the CU Boulder Data Repository (https://doi.org/10.25810/1c5d-4k36; Hilton et al., 2022). The data, plus additional spatial data on piece locations over time, will also be made available online by mid-2023 through the Caspar Creek Experimental Watersheds Phase 2 (1985–2017) data archive (3rd Edition), at https://doi.org/10.2737/RDS-2020-0018-3.

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