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Long-term dynamics of large wood in old-growth and second-growth stream reaches in the Cascade Range of Oregon

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Abstract

We quantified temporal dynamics of wood storage, input, and transport over a 24-year period in adjacent old-growth and second-growth forested reaches in Mack Creek, a third-order stream in the Cascade Range of Oregon. The standing stocks of large wood in the old-growth reach exceeded those at the second-growth reach by more than double the number of wood pieces and triple the wood volume. Annual inputs of large wood were highly variable. Wood numbers delivered into the old-growth reach were 3× higher and wood volume 10× greater than in the second-growth reach. The movement of number and volume of logs did not differ significantly between the two reaches over time. Less than 2% of the logs moved in most years, and the highest proportion moved in the year of the 1996 flood (9% in old growth and 22% in second growth). Most of the large wood aggregated as jams in both reaches. The second-growth reach lacked major jams, but 29% of the logs in the old growth were in full-channel spanning jams. Long-term observations of annual storage, input, and movement reveal the temporal dynamics of wood rather than static representations of the characteristics of wood. Input events and transport of wood in Mack Creek were episodic and varied greatly over the 24-year study, which illustrates one of the major challenges and opportunities for understanding the cumulative dynamics of wood in streams.

KEYWORDS

input, large wood, long term, movement, old growth, second growth, storage, streams

1 | INTRODUCTION

Over the last 50 years, geomorphologists and aquatic ecologists have recognized the major physical and biological roles of large wood in streams and rivers (Gurnell & Bertoldi, 2022; Ruiz-Villanueva et al., 2016; Swanson et al., 2021; Wohl et al., 2019). In the 1970s, studies first revealed critical geomorphic and ecological processes influenced by large wood in stream channels and their floodplains (Heede, 1972; Swanson et al., 1976). Early studies focused on wood abundance and the geomorphic effects of wood on channel form and hydraulics (K. J. Gregory & Gurnell, 1988; Hickin, 1984; Lienkaemper & Swanson, 1987). Soon after, ecologists began to examine the influence of wood on fish populations, organic matter storage, and macroinvertebrates (Anderson et al., 1978; Bilby & Likens, 1980; Bisson et al., 1987). Since the 1990s, research has expanded to include the importance of dead wood for terrestrial invertebrate, bird, and mammal communities in riparian areas along stream margins (Maser & Sedell, 1994; Trevarrow & Arismendi, 2022).

A number of major syntheses have integrated a complex array of global studies of large wood. One of the earliest reviews of large

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wood focused on both terrestrial and aquatic ecosystems in temperate North America (Harmon et al., 1986), followed by an international conference in 2000 to synthesize global research on wood in rivers worldwide (S. V. Gregory, Boyer, & Gurnell, 2003). Subsequently, several researchers developed comprehensive overviews of processes relevant to the dynamics of large wood and rivers (Gurnell, 2013; Gurnell & Bertoldi, 2022; Ruiz-Villanueva et al., 2016; Wohl et al., 2017, 2019). Such syntheses have greatly advanced our understanding of the substantial role of wood in rivers and provide a foundation for managing and restoring wood across river ecosystems in the future.

Recent syntheses have identified thousands of studies of wood in streams and rivers (Swanson et al., 2021), predominantly comprised of short-term (e.g., 1–5 year) studies. Such studies provide important information on specific characteristics of wood, such as the storage of wood, episodic input and transport of wood, and its effects on channel structure, habitat for fish, macroinvertebrates, and wildlife. This research has explored the effects of land use and river management on the abundance and distribution of large wood in rivers and the consequences for aquatic ecosystems. While such investigations have advanced our knowledge about the role of wood in streams and rivers, the short duration of most studies limits the understanding of the long-term loading of wood into streams and rivers and cumulative changes through time (Wohl, 2017; Yazzie et al., 2023). Our objective in this study was to quantify the characteristics of wood in the active channel and floodplain of adjacent old-growth and second-growth reaches in a third-order stream in the Cascade Range of Oregon, USA. Further, we sought to quantify the interannual dynamics of wood storage, input, and transport over a 24-year period of active monitoring. Finally, this study examines the effects of forest harvest on these characteristics and their dynamics.

2 | METHODS

2.1 | Study area

Between 1985 and 2008, we studied large wood in Mack Creek in the H.J. Andrews Experimental Forest of the Willamette National Forest in Oregon, USA. Mack Creek is a third-order tributary within the Lookout Creek catchment, the site of the long-term ecological research program (LTER) of the National Science Foundation. Mack Creek drains a 581-ha catchment at elevations ranging from 600 to 1626 m in the basaltic geology of the Western Cascades. The climate has wet winters and warm, dry summers, with an annual precipitation of approximately 2500 mm. The average annual discharge in Mack Creek from 1980 to 2019 was 0.33 m^3/s, ranging from 0.02 to a maximum of 9.8 m^3/s in 1996. Mack Creek typically has snowpack from December through March, and major floods are often associated with warm rains on snow in the transient snow zone (400–1200 m elevation; Harr, 1981). The stream channel consists predominantly of cobbles and boulders with occasional exposed bedrock (Faustini & Jones, 2003).

We investigated two reaches of Mack Creek, one surrounded by an old growth and the other located downstream in a second growth. The old-growth forest was more than 600 years old and dominated by Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*). The second growth was clearcut to the stream's edge in 1964–1965, 20 years before the start of this study. A major flood immediately following harvest potentially removed wood from the channel in addition to that removed during logging operations. The second-growth stand was dominated by young Douglas-fir and included greater abundance of red alder (*Alnus rubra*), bigleaf maple (*Acer macrophyllum*), black cottonwood (*Populus trichocarpa*), and Sitka willow (*Salix sitchensis*) than was found in the old-growth riparian forest.

The two study reaches were 120 m apart and the LTER gaging station (758 m elevation) was located between them. Widths of the floodplain and active channels were measured in the old-growth reach in 1996 following a major flood (41-year recurrence interval based on maximum annual discharges from 1980 to 2019). The average active channel width was 11.6 m in the old-growth reach and 11.0 m second-growth reach, and the average floodplain width was 14.5 m in the old growth and 10.7 m in the second growth (second-growth width from Faustini & Jones, 2003). Stream slope averaged slightly more than 9% in both reaches. Additional geomorphic details of the Mack Creek study reaches are reported in Faustini and Jones (2003).

Our study site was divided into a 670-m old-growth forest reach upstream of a 240-m second-growth stream reach (Figure 1). The lower end of the old-growth reach and Devil's Club Creek were the third-order and first-order sites of the River Continuum research project (Minshall et al., 1983). The length of the second-growth reach was determined by the harvest unit boundaries. During the first decade of the study, we extended the length of the old-growth reach by an additional 80 m to the confluence of Snag Creek, a second-order tributary of Mack Creek in the old-growth forest. The length of the old growth reach expanded from 590 m (1985) to 610 m (1986, 1988), to 660 m (1989–1995), and finally to 670 m from 1996 to 2008, with all pieces of large wood being tagged as the reach expanded. Because we calculated mean wood abundances per 100 m, the 80-m difference over the longer 670-m reach had minor effects on estimates of storage, inputs, and movement.

2.2 | Wood sampling

We tagged and inventoried all pieces of large wood (≥1 m long and ≥10 cm diameter; Swanson, Lienkaemper, & Sedell, 1976) associated with the active channel and floodplain annually from 1985 to 2008 in late October prior to winter high flows, except 1987 that was not surveyed. We measured the length and diameter of each log associated with the channel and floodplain, including portions of logs that extended up the hillslope. Each log was tagged with uniquely numbered and color-coded surface tags and four internal tags countersunk 2–4 cm on both sides at each end to allow identification after

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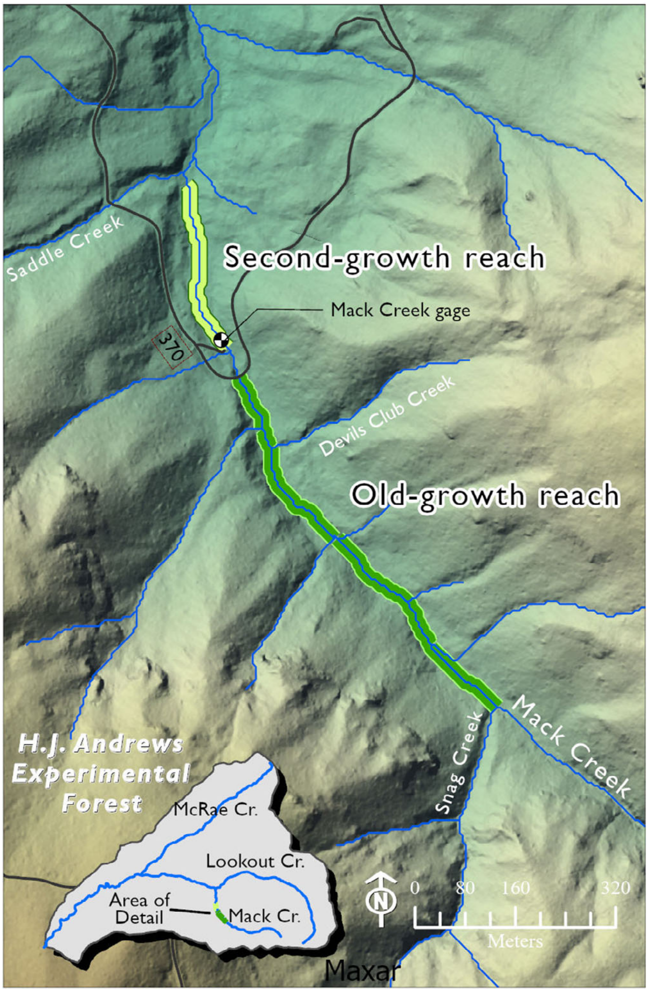

FIGURE 1 Map of the old-growth and second-growth reaches of Mack Creek in the H. J. Andrews Experimental Forest. The second-growth reach is downstream from the old-growth reach, and the gaging station is located between the two reaches. [Color figure can be viewed at wileyonlinelibrary.com]

movement or fragmentation. We recorded the location of each log within 10-m longitudinal grids based on metal fence posts installed on both banks every 20 m from the bottom of the second-growth reach to the top of the old-growth reach. The upstream-most grid was recorded as the location for logs extending across 10-m grid lines. We excluded data from the 120-m reach separating the study reaches from the analyses except for the estimation of movement distance for individual logs. The monumented 10-m grids permitted visual determination of longitudinal location during field surveys and estimation of wood movement in 10-m increments over the 1030-m study reach distance. The minimum increment for measuring distance determines the resolution of movement analyses. Because most wood pieces that moved were small and observed transport distances ranged from 10 to 600 m, the 10-m minimum distance for movement measurements was sufficient for representing the overall relationship and a smaller increment of distance would not have altered the conclusions.

Data collected for each log included dimensions (length and diameter), location, geomorphic position in the active channel and floodplain, geomorphic zone classes, decay classes, presence of a rootwad, occurrence in an accumulation, stability, and moss cover (see Appendix A in Supporting Information for detailed sampling protocols). Analyses were limited to wood that met the minimum dimensions (≥1 m long and ≥10 cm diameter) and excluded fragmented pieces that no longer met the minimum dimensions. However, we included tagged wood less than 1 m in length in the analysis of the relationship between wood length and movement distance. Geomorphic location of each log was classified by zones (Robison & Beschta, 1990). Zone 1 was the portion submerged in the wetted channel, Zone 2—exposed in active channel below bankfull depth, Zone 3—above bankfull depth including spanners above the channel, and Zone 4—on floodplain or hillslope lateral to active channel.

We used standard categories to represent the state of decay for each log. Decay classes were Class 1—bark present and firm wood, Class 2—bark loosely attached and firm wood, Class 3—wood soft in surface but firm interior, Class 4—decayed wood throughout log, Class 5—log fragments and no longer cylindrical (Robison & Beschta, 1990). We did not attempt to identify the species of wood in the field and acknowledge that different species decay at different rates and bark can fall off faster for some species than for others. Our estimates of decay class represent the overall state of decay and structural integrity of the population of wood but do not provide fine resolution measures of residence time or persistence in the channel.

New logs found during annual surveys were tagged, measured, and recorded to quantify input rates. New logs in a given location were categorized based on point of origin to differentiate between those pieces that fell into the reach from the adjacent riparian forest versus those that were transported into the reach from upstream. Logs that moved into each reach from upstream were included in the estimates of wood input. Data for logs in the channel that moved during the previous year were updated to determine movement rates and delivery into the downstream second-growth reach. Log movement was determined by changes in location in the 10-m survey grids, resulting in a minimum movement distance of 10 m.

2.3 | Environmental data

Stream discharge was measured continuously at a gaging station located at the head of the second-growth reach between the two reaches, 120 m downstream of the old-growth reach (Figure 1). We obtained daily discharge values (Figure 2) from long-term datasets in the H.J. Andrews LTER Databank (HF004). We calculated recurrence intervals based on the maximum annual discharges in Mack Creek from 1980 to 2019. The study area includes long-term environmental data on riparian reference stand composition (TV010), monumented channel cross-sections (GS002), stream discharge (HF004), water chemistry (CF002), and climate (MS001) (https://andlter.forestry.oregonstate.edu/data/catalog/datacatalog.aspx).

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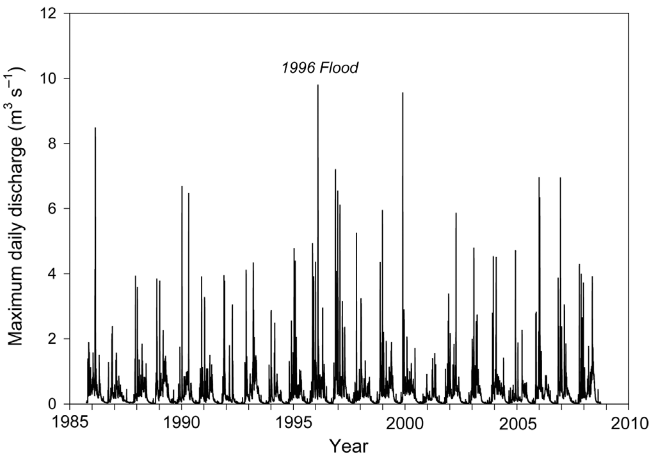

FIGURE 2 Daily maximum discharge (m^3/s) in Mack Creek from 1985 to 2008.

2.4 | Data analysis

To reduce the effects of repeated observations, we quantified characteristics of the populations of wood for each year and calculated means and variance of wood storage, inputs, numbers that moved, size classes, percent accumulation, zone locations, decay classes, and moss cover based on annual amounts for the 24-year study (no survey in 1987). Because the reach lengths for the old-growth and the second-growth forests differed, the abundance of wood was estimated per 100-m of stream length and per ha of stream area. Most of the results report the amounts and dynamics of large wood associated with both the active channel and floodplain, including portions of logs that extend beyond the channel up the hillslope. We also provide data for large wood associated only with the active (i.e., bankfull) channel by excluding wood that was only on the floodplain and did not contact the active channel (reported in Table 2).

We analyzed statistical differences between the old-growth and second-growth reaches using paired t-tests using StatGraphics (version 19). Data that were not normally distributed were transformed ($\log_e$) prior to analyses to meet the assumptions of normal distribution. The Bonferroni-corrected level of significance was set to 0.0125 ($\alpha = 0.05/4$) to account for multiple comparisons among the four measures within the categories for storage, input, moved, zones, moss cover, and decay class. We also developed exponential size class regressions for storage, input, and movers using SigmaPlot (version 15). We analyzed the relationship between the distance transported and the size of logs that moved using quantile regression (Cade & Noon, 2003) implemented in the package "quantreg" (Koenker et al., 2018) in R (version 3.6.0).

3 | RESULTS

3.1 | Wood storage

We tagged more than 2575 individual logs from 1985 to 2008 and made more than 45,000 observations of the logs and fragments of tagged logs during the annual surveys. The abundance of large wood stored in the channel and floodplain of the old-growth reach was significantly greater than the amount of wood in the second-growth reach (Figure 3). The numbers of logs per unit distance and area in the old growth (220.7 logs/100 m) were more than double those in the second growth (100.0 logs/100 m), whereas wood volume in the old-growth reach (288.4 m^3/100 m) was more than three times greater than the volume in the second growth (78.8 m^3/100 m) (Table 1). In both reaches, 5.7% of the logs had rootwads. In 1996, the largest flood during the 24-year study resulted in a 30% increase in number of logs stored in both reaches, though the increases in the volume of wood were substantially less.

3.2 | Wood input

Annual inputs of large wood into both reaches were highly variable (Figure 4). Overall, the numbers of new logs delivered into the old-growth reach were more than 1.8 times that of the second growth, and numbers per ha were almost twice the amounts in the second-growth reach (Table 1). Volume of new wood delivered to the channel was almost six times greater in the old-growth reach. A wet snowpack caused large numbers of trees to fall throughout the uplands and riparian areas of H. J. Andrews LTER site in December 1995. The increased discharge, rain on wet snow, and wind associated with the 1996 flood caused the greatest input of large wood observed over the 24 years in both study reaches (Figure 4). Inputs accounted for less than 2% of large wood storage in most years. The highest proportional inputs occurred during the winter of the 1996 flood, amounting to more than 28% of wood pieces and 15% of storage volume in the old-growth reach compared to 46% and 11%, respectively, for the second-growth reach.

Most inputs of large wood into the old-growth reach occurred as windthrow or tree fall from the adjacent riparian forest. Of the 971 pieces of new wood delivered into the 690-m old-growth reach, 57% originated from tree falls from the adjacent forest and 43% was transported into the reach from upstream. We observed only two logs transported out of Devil's Club Creek into the old-growth reach during the study. In the second-growth reach downstream, 13% of the 220 new logs originated from the adjacent young forest, and almost all were small pieces, while 87% was transported from upstream. Because of the young age of trees in the second-growth forest, new wood from the adjacent riparian stand was a small portion of the wood input during our study period. Bank erosion provided very little wood input from the adjacent forest in either reach.

3.3 | Wood movement

Similar to the episodic nature of wood inputs, annual wood movement rates in both reaches were highly variable (Figure 5). The number and volume of logs moved per 100 m in the two reaches did not differ significantly. An average of 1.9% of pieces moved in the old-growth reach and 3.4% in the second-growth reach, but this difference was

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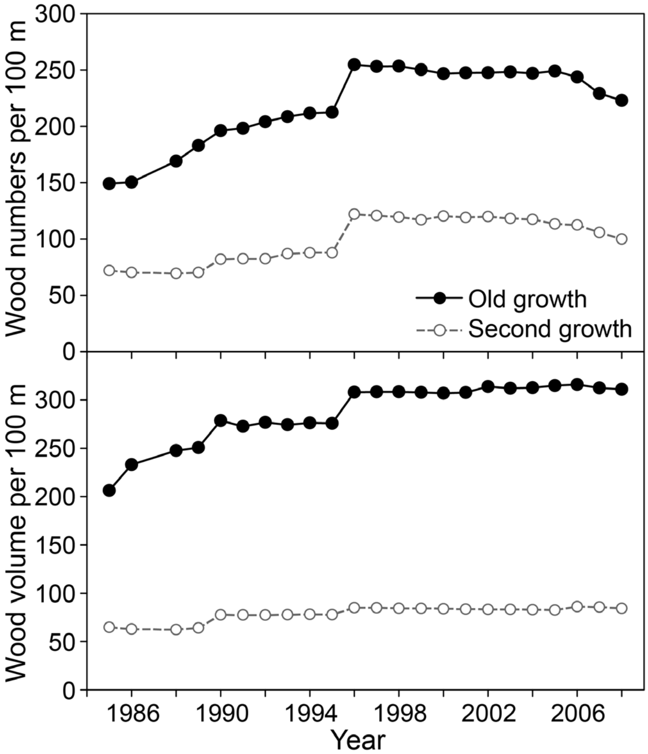

FIGURE 3 Numbers and volumes of large wood storage per 100 m in the old-growth and second-growth reaches of Mack Creek from 1985 to 2008.

not significant because of the high interannual variability (Table 1). Less than 2% of the logs moved in most years, and the highest proportion moved in the year of the 1996 flood (8% and 22% in the old growth and second growth, respectively). We observed an abrupt decrease in moss cover following the largest flood in 1996. Logs with less than 5% moss cover increased from an average of 35% to an average of 55% of the logs in the old-growth reach and from 40% to 62% in the second-growth reach after the flood. This loss of moss cover resulted from scour during the flood and input of new wood lacking moss. The greater proportion of logs with low moss cover in the second-growth reach potentially reflects transport as a source of logs in this reach.

The distance moved by logs decreased with increasing wood length in both reaches (Figure 6). Most of the wood that moved in Mack Creek was relatively small. In the old-growth reach, 71% of the pieces that moved were 2 m or less in length, and 59% were 2 m or less in the second-growth reach. The longest piece that moved in the old-growth reach during the 24 years was 14 m, which represents the upper limit for approximately 90% of the total storage. In contrast, the longest log that moved in the second-growth reach was only 5.1 m, representing 72% of storage. Active channel width averaged 12 m in the old-growth reach and 11 m in the second growth, and only one of the 885 recorded log movements was longer than the active channel width.

The number of logs that were entrained into transport annually was related exponentially to the maximum discharge (Figure 7). The

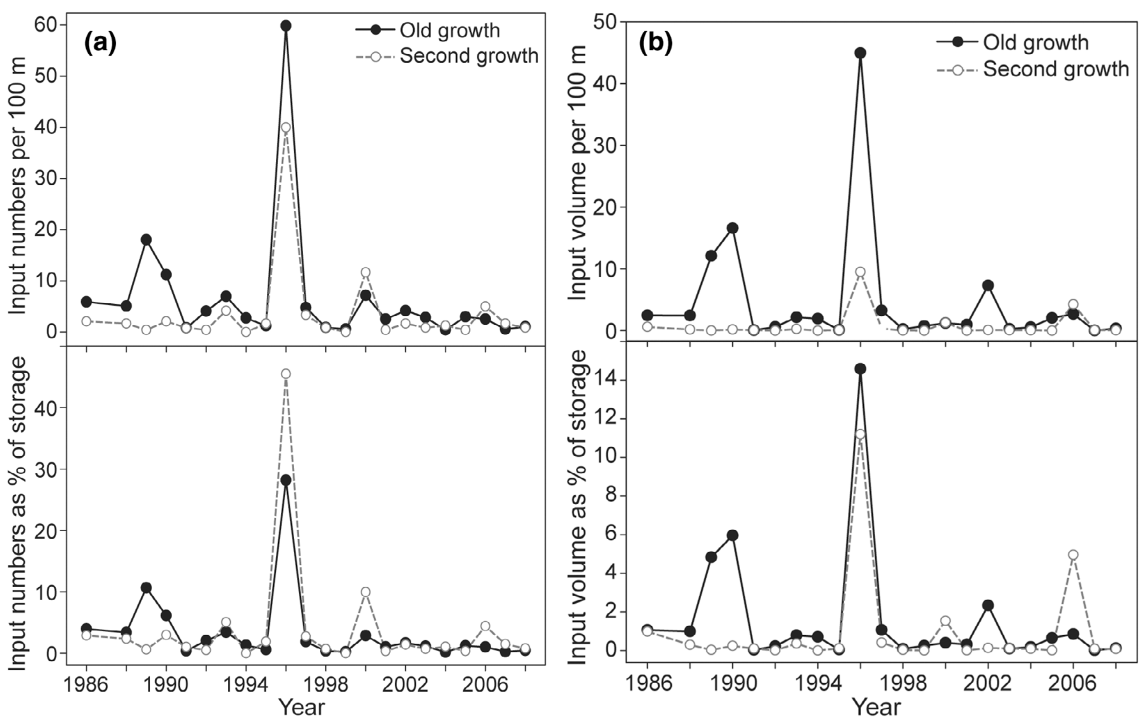

FIGURE 4 Numbers of large wood inputs per 100 m and input numbers as a percent of numbers in storage (a) and volumes of inputs of large wood inputs per 100 m and input volumes as a percent of volumes in storage (b) in the old-growth and second-growth reaches of Mack Creek from 1986 to 2008.

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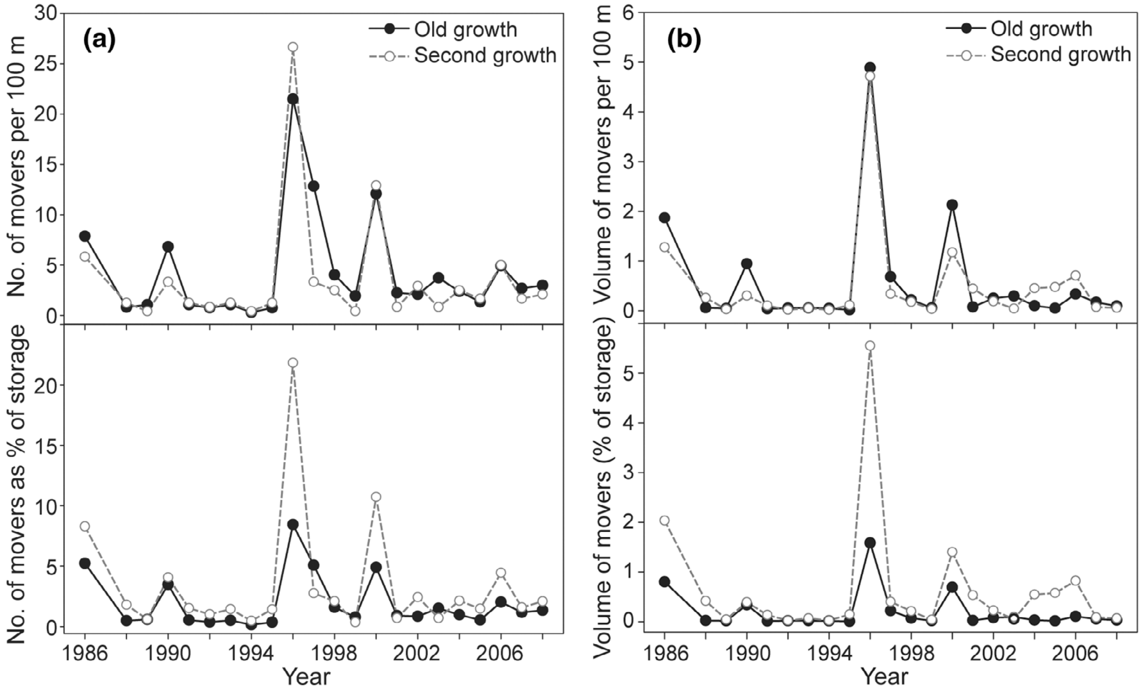

FIGURE 5 Numbers of large wood per 100 m and percent of wood storage (a) and volumes per 100 m and percent of storage (b) that moved annually in the old-growth and second-growth reaches of Mack Creek from 1986 to 2008.

movement rates were extremely low until maximum annual discharges of 4 m^3/s, after which the number of logs transported annually increased rapidly with greater annual maximum discharge. Sizes of wood that moved differed as a function of discharge. In 1997 (annual maximum discharge 7.02 m^3/s), the number of logs that moved was greater than would be expected from the exponential curve. This year with relatively high discharge immediately followed the year with the highest discharge event during our study period, which may have deposited unstable pieces that moved in subsequent years. Increasing numbers and longer pieces of wood were transported in floods of longer recurrence intervals (Figure 8).

3.4 | Wood size distribution

The size class distributions in the two reaches of Mack Creek exhibited strong J-shaped size class distributions (Figure 9). The distributions were similar for wood less than 15 m in length in both reaches, but the old-growth reach contained longer pieces, which would be expected given the taller trees in the old-growth forest. Maximum tree heights were up to 100 m in the old-growth forest versus 30 m in the second growth. The maximum length of wood in the second growth reach was 15.6 m with the exception of two logs (33 and 34.8 m). The old-growth reach contained larger pieces with 76 logs from 15 to 51 m in length, and a median length in the old growth of 2.7 m. The median length in the second-growth reach was 2.3 m but contained only two logs longer than 15.6 m. The size frequency for wood input during the 24-year study was smaller than the size frequency of wood in storage. The slope of the size distribution of logs that moved was skewed to even shorter lengths.

3.5 | Characteristics of wood

Most of the length of volume of logs occurred within geomorphic Zones 2 and 4, and a small fraction of the length or volume of logs was inundated at low flow in Zone 1 (Table 1). The proportion of the wood length in Zones 1 and 2 was greater in the old growth (51%) than in the second growth (32%), but a higher proportion of the wood length occurred on the floodplain (Zone 4) in the second growth (65% vs. 44%). The proportion of volume was even greater for the zone outside the active channel, with 74% in Zone 4 in the second growth in contrast to 41% in the old growth. Only 27% of the wood volume occurred in Zones 1 and 2 in the old growth versus 17% in the second growth.

Most of the wood occurred in accumulations of three or more pieces in both reaches (Table 1). In the old growth, 78% of all pieces occurred in accumulations in contrast to 57% of the pieces in the second growth. Approximately 15 accumulations per 100 m were found in the old growth and six accumulations per 100 m in the second-growth reach. Though we found numerous accumulations in the second-growth reach, there was only one small full channel jam with less than 10 wood pieces. Four of the accumulations in the old growth were major jams with more than 100 pieces of large wood and 29% of the logs were in full-channel spanning jams.

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TABLE 1 Means (±SD) of large wood characteristics in both the active channel and floodplain of old-growth and second-growth reaches of Mack Creek in annual surveys from 1985 to 2008.

Characteristic	Measure	Old growth	SD	Second growth	SD	*p* Value
Area						
Active channel	ha	0.75		0.26		
Floodplain	ha	0.19		0.04		
Total	ha	0.94		0.30		
Storage						
Number	#/100 m	**220.7**	33.7	**100.0**	19.8	<0.001
	#/ha	**1548.3**	287.3	**812.4**	161.1	<0.001
Volume	m^3/100 m	**288.4**	30.5	**78.8**	7.8	<0.001
	m^3/ha	**2019.7**	290.5	**640.8**	63.4	<0.001
Input						
Number	#/100 m	**6.7**	12.6	**3.7**	8.5	0.020
	#/ha	47.0	89.6	30.0	69.0	0.059
Volume	m^3/100 m	**4.7**	9.9	**0.8**	2.2	0.001
	m^3/ha	**33.2**	70.5	**6.4**	17.5	<0.001
Moved						
Number	#/100 m	4.3	5.2	3.6	5.8	0.056
	#/ha	30.6	36.9	29.2	47.2	0.354
Volume	m^3/100 m	0.6	1.1	0.5	1.0	0.906
	m^3/ha	4.0	8.0	4.1	8.2	0.449
Size						
Length	Mean	**4.39**	0.16	**3.23**	0.21	<0.001
	Median	**2.67**	0.14	**2.28**	0.11	<0.001
Volume	Mean	**1.30**	0.09	**0.78**	0.09	<0.001
	Median	**0.18**	0.03	**0.21**	0.05	<0.001
Rootwads	Percent	5.7	0.2	5.8	1.0	0.408
Accumulation	Percent	**78.3**	1.0	**57.3**	6.2	<0.001
Zones						
Length						
Zone 1	Percent	**5.2**	0.3	**2.2**	0.2	<0.001
Zone 2	Percent	**45.8**	1.3	**30.2**	3.1	<0.001
Zone 3	Percent	**5.2**	0.3	**2.2**	0.2	<0.001
Zone 4	Percent	**44.0**	1.7	**65.4**	3.3	<0.001
Volume						
Zone 1	m^3/100 m	**7.3**	0.6	**1.1**	0.3	<0.001
Zone 2	m^3/100 m	**70.3**	7.3	**12.6**	1.6	<0.001
Zone 3	m^3/100 m	**93.2**	13.6	**6.7**	1.1	<0.001
Zone 4	m^3/100 m	**116.9**	10.5	**58.4**	5.6	<0.001
Zone 1	Percent	**2.5**	0.1	**1.3**	0.3	<0.001
Zone 2	Percent	**24.5**	0.9	**16.0**	0.9	<0.001
Zone 3	Percent	**32.3**	1.4	**8.5**	0.9	<0.001
Zone 4	Percent	**40.8**	1.3	**74.2**	1.5	<0.001
Stability	Percent	**57.3**	4.5	**46.6**	10.3	<0.001
Moss cover						
Cover Class 1	Percent	**45.4**	10.3	**52.0**	10.6	<0.001
Cover Class 2	Percent	**13.7**	1.3	**21.0**	4.5	<0.001
Cover Class 3	Percent	**22.8**	5.5	**19.7**	5.9	<0.001
Cover Class 4	Percent	**18.1**	3.8	**7.2**	2.4	<0.001

(Continues)

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TABLE 1 (Continued)

Characteristic	Measure	Old growth	SD	Second growth	SD	*p* Value
Decay class						
Decay Class 1	Percent	**12.5**	5.7	**3.6**	3.3	<0.001
Decay Class 2	Percent	**21.9**	2.1	**10.7**	10.4	<0.001
Decay Class 3	Percent	**54.2**	4.4	**73.8**	8.6	<0.001
Decay Class 4	Percent	11.4	2.0	11.8	2.1	0.150

Note: Values for wood data reported in bold are statistically significantly different between old growth and second growth (paired *t*-test; a Bonferroni correction of $\alpha = 0.0125$ was applied to all tests per category).

TABLE 2 Means (± SD) of large wood characteristics in the active channel of old-growth and second-growth reaches of Mack Creek from 1985 to 2008.

Characteristic	Measure	Old growth	SD	Second growth	SD	*p* value
Area						
Active channel	ha	0.75		0.26		
Floodplain	ha	0.19		0.04		
Total	ha	0.94		0.30		
Storage						
Number	#/100 m	**183.6**	25.9	**60.1**	14.2	< 0.001
	#/ha	**1604.5**	281.1	**562.1**	133.1	< 0.001
Volume	m^3/100 m	**241.9**	27.1	**27.8**	2.7	< 0.001
	m^3/ha	**2112.5**	315.0	**259.4**	25.1	< 0.001
Input						
Number	#/100 m	5.6	11.1	3.5	7.9	0.104
	#/ha	39.8	79.2	28.6	64.0	0.292
Volume	m^3/100 m	**4.0**	8.5	**0.7**	1.7	0.008
	m^3/ha	**28.2**	60.4	**5.5**	14.1	0.002
Moved						
Number	#/100 m	4.3	5.1	3.3	4.9	0.485
	#/ha	37.8	45.7	31.2	45.9	0.122
Volume	m^3/100 m	0.6	1.1	0.5	0.9	0.913
	m^3/ha	5.0	9.9	4.5	8.5	0.667
Size						
Length	Mean	**4.45**	0.14	**2.79**	0.25	< 0.001
	Median	**2.67**	0.12	**2.13**	0.09	< 0.001
Volume	Mean	**1.32**	0.07	**0.48**	0.08	< 0.001
	Median	**0.17**	0.03	**0.12**	0.04	< 0.001
Rootwads	Percent	**5.6**	0.2	**6.1**	1.1	0.025
Accumulation	Percent	**81.0**	1.2	**50.8**	8.3	< 0.001
Stability	Percent	52.4	5.0	51.8	12.0	0.721
Moss Cover						
Cover class 1	Percent	**46.8**	10.3	**57.3**	16.6	< 0.001
Cover class 2	Percent	**14.3**	1.2	**21.3**	6.0	< 0.001
Cover class 3	Percent	**21.7**	5.6	**17.7**	9.1	< 0.001
Cover class 4	Percent	**17.2**	3.9	**3.7**	2.0	< 0.001
Decay class						
Decay class 1	Percent	**12.4**	5.7	**4.6**	4.2	< 0.001
Decay class 2	Percent	**23.0**	2.3	**14.6**	10.4	< 0.001
Decay class 3	Percent	**55.5**	4.4	**74.2**	13.2	< 0.001
Decay class 4	Percent	**9.1**	2.3	**6.7**	1.7	< 0.001

Note: Values for wood data reported in bold are statistically significantly different between old growth and second growth (paired *t*-test; a Bonferroni correction of $\alpha = 0.0125$ was applied to all tests per category).

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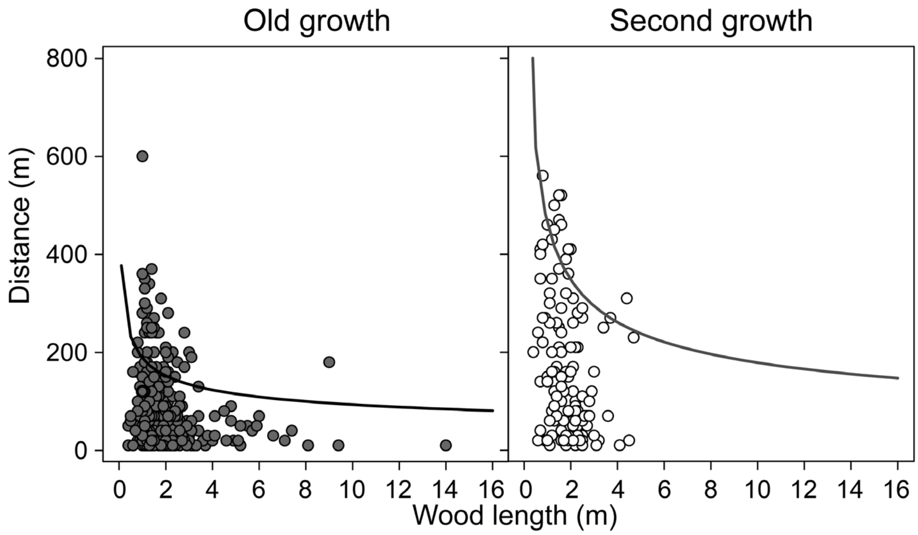

FIGURE 6 Distance moved as function of wood length in the old-growth and second-growth reaches of Mack Creek from 1986 to 2008. The line represents the 90th quantile of wood that moved in the old-growth and second-growth reaches. The analysis includes pieces that fragmented into sizes less than 1 m in length. Data for old growth are logs that moved within the old-growth reach; second growth includes logs that originated in either reach and ended in the second-growth reach.

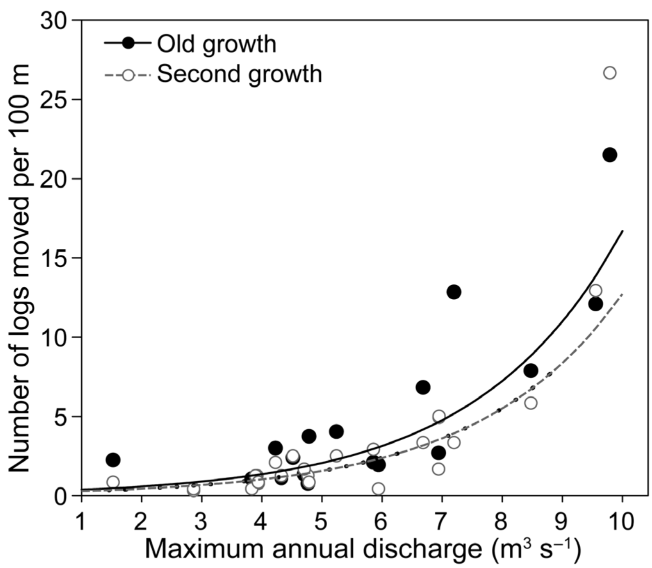

FIGURE 7 Number of logs that moved as an exponential function of maximum annual discharge (m^3/s) in the old-growth ($a = -1.18$, $b = 0.41$) and second-growth ($a = -1.20$, $b = 0.38$) reaches of Mack Creek from 1986 to 2008. Curves are based on an exponential growth equation ($Y = \exp(a + b^*X)$).

Most of the wood in both reaches was in Decay Class 3, indicating some degree of decomposition on the surface, but still relatively firm. The proportion of firm wood in Decay Classes 1 and 2 was greater in the old growth (34%) than in the second growth (14%), reflecting the lack of recent delivery of large trees in the second growth. Older decayed wood in Decay Class 4 was similar in the old growth and second growth, which may result from the low persistence of decayed wood during floods in both reaches.

Many wood studies do not account for wood outside the active channel, but still within the floodplain. The results reported above included wood in both the active channel and floodplain. To estimate storage, input, and movement for logs only associated with the active channel, we excluded logs located only on the floodplain (Table 2). These estimates included logs that extended from the active channel onto the adjacent floodplain or hillslope. Comparisons of wood characteristics in the active channel alone did not substantially change the statistical differences observed between the old-growth reach and the second-growth reach for the active channel and floodplain.

4 | DISCUSSION

One of the unique aspects of our study of large wood in a third-order stream in the Pacific Northwest of North America is the multidecadal length of the annual surveys of wood storage, input, and movement. We are aware of several other studies of wood dynamics in streams that encompass more than a decade, including a 12-year study in the Oregon Coast Range (Yazzie et al., 2023), a 14-year study in Michigan (Bosio et al., 2021), a 20-year study in Casper Creek at the coast of northern California (Lininger & Hilton, 2022), and a study in British Columbia that spanned 43 years in Carnation Creek, British Columbia (Reid & Hassan, 2020). Our study includes both an undisturbed old-growth forest and a second-growth forest during the period from 21 to 44 years after forest harvest. The study in Michigan included three streams that had been logged in the late 1800s, each of which contained reference reaches and 100-m wood addition reaches. The study of Casper Creek included biennial surveys of two tributaries harvested in the late 1800s and were harvested again in the 1970s and late 1980s. The Carnation Creek study spanned a period from 1991 to 2017 with annual surveys in most years for eight reaches of the lower 3 km of channel. Similar to our study in Mack Creek, the Carnation Creek study included both undisturbed old-growth and second-growth forests soon after harvest. Though the disturbance history, channel geomorphology, hydrologic regimes, and species composition and ages of the riparian and catchment forests differed, these long-term studies of large wood shared several common findings.

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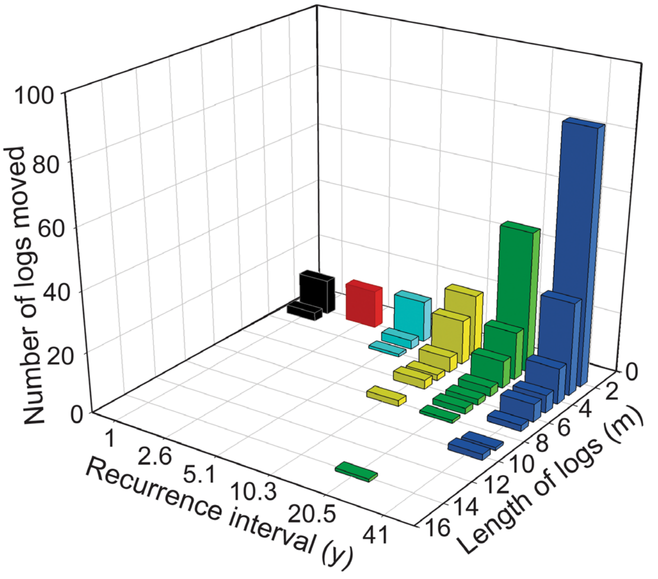

FIGURE 8 Number of logs in different wood size classes that moved in the old growth reach during years of selected recurrence intervals—2001–1.0 year, 1999–2.6 year, 2007–4.6 year, 1986–8.2 year, 2000–13.7 year, 1996–20.5 year. Recurrence intervals based on annual maximum discharges in Mack Creek from 1980 to 2019. [Color figure can be viewed at wileyonlinelibrary.com]

The amount of wood in the active channel (2112 m^3/ha) or combined active channel and floodplain (2020 m^3/ha) of the old-growth reach in Mack Creek is in the upper range of wood observed in streams surrounded by coniferous forests (Cordova et al., 2007; Gurnell & Bertoldi, 2022; Ruiz-Villanueva et al., 2016; Wohl et al., 2017). Delivery of wood into the third-order stream from the adjacent 600-year-old forest coupled with low transport of the available storage resulted in the very high abundance of wood (see photographs of Mack Creek in Appendix B of Supporting Information). Additionally, our measurements include wood on the floodplain, spanners that are above bankfull channel depth, and portions of wood that extend up the adjacent hillslopes. The higher volume per ha in the active channel than in the combined active channel and floodplain illustrates the higher density of wood in the active channel. Scott and Wohl (2018) reported that wood abundances in streams in Washington were greater with greater jam densities. Jam densities in Mack Creek are high compared to other studies. The values we reported for wood abundance differ somewhat from other studies of wood in Mack Creek (Faustini & Jones, 2003; Gurnell et al., 2002; Lienkaemper & Swanson, 1987; Nakamura & Swanson, 1993). These differences in reported abundances are related to the different time periods, channel lengths, size criteria for large wood, inclusion of wood on floodplains and hillslopes, and use of selected geomorphic zones. Many studies of wood in streams are in landscapes where riparian forests are greatly modified by land use practices (Wohl, 2014), thereby reducing wood loads as we observed in the downstream second-growth reach. We were fortunate to study two reaches of vastly different forest age for nearly a quarter of a century to compare wood dynamics.

As demonstrated in our 24-year study, the size of wood in streams reflects the composition of the riparian forest, and the

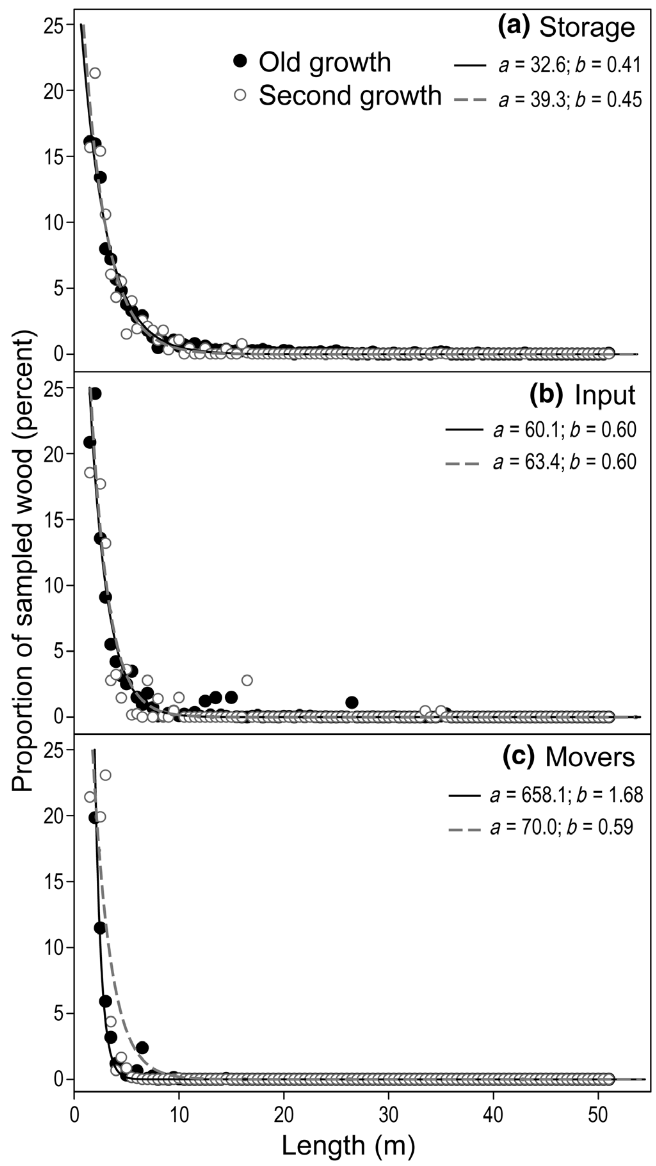

FIGURE 9 Percent of size classes of total large wood storage, input, and movers per 100 m in the old-growth and second-growth reaches of Mack Creek from 1985 to 2008. Curves are based on an exponential decay equation ($Y = a^*\exp(-b^*X)$).

movement and retention of wood is a function of the size of wood in the channel (Bosio et al., 2021; Braudrick & Grant, 2000; Ruiz-Villanueva et al., 2014). As a result, wood loading is strongly related to the surrounding riparian forests and upstream forests in the catchment, and forests with larger trees, such as Douglas-fir, hemlock, and western redcedar in Mack Creek, often exhibit much higher amounts of wood than other riparian types (Gurnell & Bertoldi, 2022; Harmon et al., 1986). We observed that wood size was largest for wood stored in the channel and floodplain, somewhat smaller for input from the riparian forest, and even smaller for wood in transport (Figure 9). The smaller median size of input as compared to storage possibly reflects the transport of the smaller wood after delivery into the channel (Reid & Hassan, 2020). Forests of different regions inherently create different amounts of wood storage and exert different effects on

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channels and floodplains (Cordova et al., 2007; Gurnell et al., 2002; Wohl et al., 2017).

Most of the wood length in Mack Creek was in the active channel, but the highest proportion of volume of individual logs was found in Zone 4 adjacent to the active channel on the floodplain or hillslope. Wood abundances in this study also included wood stored on the floodplain, but many analyses of wood in streams are limited only to the wetted or active channel, and accordingly miss a major portion of the wood in the stream network. Large floods mobilize wood on the floodplain and deliver it to the active channel (Comiti et al., 2016; Gurnell, 2003; Wohl, 2020), as we observed in the series of floods over our study period. Understanding the dynamics of wood in streams requires a broader perspective of stream channels that includes assessments of both active channels and their floodplains (Collins et al., 2012; Sear et al., 2010; Sutfin et al., 2016; Wohl, 2013; Lininger et al., 2017).

Measurement of rates of wood input into stream channels and floodplains is extremely challenging and requires adequate spatial and temporal scales to represent delivery processes, such as tree fall or wind throw, flooding, snow and ice loads, delivery from hillslopes by landslides and debris flows, and wildfire (Benda et al., 2003; Collins et al., 2012; Nakamura & Swanson, 2003). Early studies of wood input examined the spatial aspects of wood input (McDade et al., 1990) and the effects of input processes on the sizes of wood in channels (Sobota et al., 2006; Van Sickle & Gregory, 1990). Wood delivery from upstream and upslope is not limited to the riparian forests, as landslides and debris flows can deliver large amounts of wood at points along the stream network (Benda & Sias, 2003; Lamberti et al., 1991; May & Gresswell, 2003). Several mechanistic models have been developed to represent the delivery of wood from riparian areas based on riparian and upslope forest composition and potential rates of stand mortality or disturbance (Acker et al., 2003; Benda & Sias, 2003; Meleason et al., 2003; S. V. Gregory, Meleason, & Sobota, 2003; Welty et al., 2002). In Mack Creek, most wood inputs occurred in years with large floods, but in the water year of 1995–1996, an average of almost 60 pieces of wood/100 m entered the channel in the old growth. However, much of this input was not directly related to the February flood. A wet snowpack on saturated soils caused large numbers of trees to fall over throughout the area in December 1995, leading to high rates of delivery. Our measurement of annual wood delivery only represents a single type of delivery in a wet coniferous forest of the Pacific Northwest and we did not observe mass inputs or major bank erosion during the study period. Lininger and Hilton (2022) observed input rates from 0.05 to 1.78 m^3/100 m in a 20-year study of two second-growth forest reaches in northern California, considerably lower than the average of 4.7 m^3/100 m we observed in the old-growth reach of Mack Creek, but similar to the 0.8 m^3/100 m we found in the second-growth reach. Quantifying long-term rates and patterns of wood inputs, which determine the amounts of wood observed in streams and rivers, remains a major research challenge.

Volumes of wood observed in streams reflect the history of input and movement. The observed input rates and storage of wood permit estimation of the turnover time, or the time required to accumulate the amount of wood in the channel. Based on our 24-year study, the turnover rate of wood in the old-growth reach is 1.62%, thereby requiring 62 years to accumulate the observed wood abundance from both input from the adjacent forest and transport from upstream. Because input from the adjacent riparian forest and upstream were approximately equal in this reach, it would require approximately 125 years to attain the wood loads solely through riparian delivery. The turnover rate in the second growth was 0.68%, requiring 146 years to attain the observed abundance, reflecting the low rates of wood input from the adjacent riparian forest and stronger dependence on transport from upstream. Meleason et al. (2003) developed a mechanistic wood model based on the composition of the old-growth riparian reference stand in Mack Creek and estimated that approximately 400 years would be required to attain the maximum riparian tree volume and approximately 450 years to attain the maximum wood load. The lag in the riparian forest development and maximum wood abundance is generally consistent with the empirically determined rates of turnover observed in Mack Creek. Other field studies (Lininger & Hilton, 2022; Livers et al., 2018) and simulation models (Reid & Hassan, 2020) have found turnover times of 100 to 200 years are required to replace the wood stored in streams of western North America. Such lags between forest development and increases in wood abundance in stream channels have been demonstrated by a broader trend on federal lands across the Pacific Northwest following the implementation of the Northwest Forest Plan. Monitoring over the three decades since 1994 shows an increasing amount of large trees in riparian areas but a decline in the amount of large wood in channels, reflecting the legacy of land use management and time lags (Dunham et al., 2023).

Wood movement greatly alters the spatial distribution of wood in streams. In the old-growth reach, an average of 1.9% of the logs in the old-growth reach and 3.4% in the second-growth reach moved annually. Prior to our study, Lienkaemper and Swanson (1987) mapped and resurveyed large wood from 1975 to 1984 in five first-order to fifth-order streams in the H.J. Andrews Experimental Forest. They found that movement rates ranged from 0.7% to 8.2% per year averaged over the study duration and generally increased with channel width. Lienkaemper and Swanson (1987) estimated that 5% of the mapped logs in Mack Creek moved per year. Lininger and Hilton (2022) similarly found that a small proportion (12%) of the logs did not move during their 20-year study. Yazzie et al. (2023) surveyed wood >3 m in length and >0.3 m in diameter for 8 years over a 12-year period in 65 km of a coastal river in Oregon. Wood in the Elk River catchment exhibited higher variation in annual storage than in Mack Creek. The coefficient of variation in storage for the mainstem Elk River and six tributaries ranged from 25% to 68% as compared to 19% and 20% in the old-growth and second-growth reaches of Mack Creek. They found the greatest change in wood storage after the 1996 flood, the same event for which we observed our greatest wood movement rates. Wood storage increased after that flood in Mack Creek, which also occurred in two of the six tributaries in the Elk River study (Yazzie et al., 2023).

Several field and laboratory studies have demonstrated that wood length is a major determinant of the distance wood moves in transport, and the ratio of the length of the wood to the width of the

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channel is a major determinant of the distance moved in a specific stream (Braudrick & Grant, 2000; Lienkaemper & Swanson, 1987; Ruiz-Villanueva et al., 2013). The mapping study in Mack Creek by Lienkaemper and Swanson (1987) observed that all logs that moved were shorter than the active channel width. In Mack Creek, only one (14 m) of the 410 logs that moved during the 24 years was longer than the average active channel width (11.5 m), and the sizes of transported wood that moved increased with greater discharges and flood recurrence intervals. The very large pieces of wood as well as the wood stored on the floodplain were much less likely to move than smaller pieces in the active channel. As a result, only 9% of the wood in the old growth moved during the year of the largest flood, which had a recurrence interval of 20.5 years. In the same event, 23% of the wood in the second-growth channel was transported. Gurnell et al. (2002) presented data on wood movement in Mack Creek during the early portion of this study (1985–1996), and subsequent models of wood dynamics in other regions noted the similarity of model results to the data from Mack Creek (Eaton et al., 2012). Wood density was negatively associated with active channel width in a coastal river in Oregon, which they attributed to lower retention with increasing channel width (Yazzie et al., 2023). Watershed studies in Japan revealed that the ratio of wood length to channel width was a major determinant of wood movement and that transport caused fragmentation, leading to smaller piece sizes through time (Seo & Nakamura, 2009). In annual surveys of large wood in reaches of Carnation Creek, more than 60% of logs longer than bankfull width remained after 9 years, but only about 30% for those that were less than half of the bankfull width (Reid & Hassan, 2020). Bosio et al. (2021) evaluated large wood (2.5 m in length; 0.5 m in diameter) added to three streams in Michigan and measured movement annually for 14 years. Of the 75 logs added, 41 moved an average of 4.0 m during floods. Lininger and Hilton (2022) found that smaller logs moved more frequently. Many studies have observed substantial movement of wood during floods, but few include long-term observations to quantify the relative frequency and magnitude of wood transport.

Studies of ancient forests offer unique laboratories for exploring the characteristics of wood in streams. Most wood in stream channels is found in accumulations, and Gurnell et al. (2022) used a series of investigations of wood in the New Forest (28,925 ha) in England to measure rates of change in wood accumulations between 1991 and 2021. The New Forest, as would not be expected from its name, was created in 1079 by William the Conqueror. This ancient forest has been used for hunting, livestock grazing, and firewood for centuries, which modified the structure of this old forest landscape. In two stream reaches (F and G) similar to the width of Mack Creek, Gurnell et al. (2022) found an average of 5.2 jams/100 m, which is similar to the density of jams we observed in the second-growth reach (5.8 jams/100 m) in Mack Creek but roughly one-third of the 14.7 jams/100 m in the old-growth reach. The difference reflects the relative ages and composition of these old forests with different land use histories. However, the proportions of full channel spanning jams and partial lateral jams were similar, with 20% of all jams in full and 80% in partial jams in Mack Creek and 27% in full and 73% in partial jams in the New Forest.

In Mack Creek, 78% of the wood occurred in jams in the old growth and 57% in the second growth. In Carnation Creek, 80% of the large wood occurred in jams. Two accumulations accounted for 30% of the wood in 65 km of a coastal river and its tributaries (Yazzie et al., 2023). Wood jams contained 68% of the large wood in streams in old-growth forests in Michigan (Morris et al., 2007). Wohl and Cadol (2011) found that jams contained an average of 46% of the wood in four channel segments in second-growth forests in Colorado, with an average spacing of 5.4 jams/100 m. This spatial distribution was similar to that of the second-growth reach in Mack Creek, the New Forest, and systems in Michigan (3.3 jams/100 m; Morris et al., 2007) and Argentina (6.1 jams/100 m; Mao et al., 2008). Wohl and Cadol (2011) noted the wood loads in the Colorado stream segments were lower than streams in the Pacific Northwest (Gurnell et al., 2002). The higher abundance in the old-growth reach of Mack Creek possibly is related to the high jam density (Scott & Wohl, 2018). The probability of logs interacting increases as spatial density or wood abundance increases, and the high density of large jams potentially retains wood in transport more effectively. While small jams of three or more logs in Mack Creek spaced less than 10 m apart, four large, channel-spanning jams of more than 100 logs occurred in the old-growth reach, spaced an average of 200 m apart. Large aggregations would be expected to be spaced farther apart because of the greater likelihood of forming smaller accumulations laterally or within channels and the geomorphic constraints of forming and maintaining full channel accumulations.

At a global scale, land use practices have extensively altered the composition and age of forests in the catchments that provide wood to streams and rivers, directly modifying the amounts, sizes, and species of wood. Reviews of wood research have clearly documented the lower amounts of wood stored in second-growth forests and agricultural and urban land (Gurnell, 2013; Gurnell & Bertoldi, 2022; Harmon et al., 1986; Ruiz-Villanueva et al., 2016; Wohl et al., 2017, 2019). The lower abundance in the second-growth reach in Mack Creek is consistent with the observed effects of land use, and the lower rates of input and a higher proportion of transported wood illustrate mechanisms responsible for reduced wood loading. Other long-term field studies of large wood (Lininger & Hilton, 2022; Morris et al., 2010; Reid & Hassan, 2020) and computer simulations (Eaton et al, 2012; Meleason et al., 2003) have documented the strong influence of forest composition and age on wood loading into streams. Conservation strategies that maintain existing mature riparian forests have a greater influence on amounts of wood in streams than restoration practices to replace wood that has been lost by riparian forest harvest or stream clearing (Grabowski et al., 2019; Gurnell et al., 1995).

Restoration of wood in streams and rivers commonly adds wood to stream channels to replace that removed by land use or channel modification. Artificial additions of wood can restore physical and biological functions in the short term (Roni et al., 2015), but do not restore the processes that deliver wood to streams over the long term. In such cases, the transport of wood out of the reach and decomposition will gradually reduce the initial amounts of wood (Bosio et al., 2021). The use of wood with rootwads can reduce the mobility of wood, but as our study demonstrates, only partially

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compensates for transport loss because the proportion of wood with rootwads is less than 10% of the wood even in streams in older forests. Attempts to retain wood artificially by cabling and anchoring reduces movement but creates unnatural dynamics, negates many of the intended functions, and causes additional safety concerns. Riparian and upslope silviculture are required to restore the long-term sources of wood and its physical and biological functions (Boyer et al., 2003), but restoration of mature forests requires many decades or centuries in most landscapes. The temporal contrast between the artificial addition of wood and the restoration of natural sources of wood demonstrates the tendency for short-term wood restoration to lead to gradual habitat degradation when riparian forests are not allowed to recover to mature forest conditions (Bisson et al., 2003; Boyer et al., 2003; Grabowski et al., 2019).

5 | CONCLUSIONS

Long-term observations of annual storage, input, and movement reveal the dynamics of wood rather than static representations of the characteristics of wood. In Mack Creek, both input events and transport of wood were episodic and varied greatly over the 24-year study. Even the length of this study is very short within the temporal context of old-growth forest development and episodic catastrophic events that deliver extremely large volumes of wood, such as landslides, debris flows, floods of greater than 100-year recurrence intervals, and wildfires. Such major events are directly relevant to future research in Mack Creek. In August 2023, more than 70% of the H.J. Andrews Experimental Forest and essentially all of the Mack Creek catchment burned in a 10,400-ha forest fire (https://andrewsforest.oregonstate.edu/about/news-events/lookout-fire-updates-2023). Future surveys in Mack Creek will provide additional information on the consequences of the amounts and dynamics of wood in streams in old growth and harvested forests.

Stochastic disturbances and associated input and transport processes create major challenges for understanding the cumulative dynamics of wood in streams. Many studies survey the characteristics of wood in multiple streams, which provides an understanding of the spatial variation of wood in stream networks. To a limited degree, this reflects the consequence of temporal variation because all study streams do not necessarily experience the same disturbances and delivery events, but the observed variation cannot be attributed to input processes. A combination of short-term site-specific studies, studies of multiple streams, and long-term studies of either single or multiple streams have contributed to a more robust understanding of wood in streams (Gurnell, 2013; Gurnell & Bertoldi, 2022; Ruiz-Villanueva et al., 2016; Wohl et al., 2019). While multiple long-term studies of wood dynamics are possible, the logistical challenges of conducting annual measurements of long reaches of multiple streams limit the feasibility of this approach. Dahlström et al. (2005) used dendrochronology to determine dates of wood inputs, which is less precise than direct observation but provides estimates of inputs over centuries. Another alternative is long-term observations of short-reaches of multiple streams, but the reaches of each site must be sufficiently long to capture the distribution of input processes and distance of wood movement. Models of wood dynamics offer quantitative approaches to investigate long-term dynamics of wood input processes, storage, and transport based on the growing body of short-term investigations (S. V. Gregory, Meleason, & Sobota, 2003; Ruiz-Villanueva et al., 2014).

Researchers have made major advances in understanding the physical and ecological roles of wood in streams and rivers. Increased attention to long-term dynamics of large wood would strengthen our understanding of temporal processes that determine the amounts and distributions. Future climate change will alter forest growth and survival, disturbances (e.g., drought, fire, insect outbreaks), recolonization, and regional shifts in forest composition. Anticipating the effects of climate change on large wood dynamics raises many important questions for future research and monitoring. How will wood recruitment and stream movement processes change with climate? How will abundances of legacy wood affect the resilience and resistance of stream ecosystems to rapid climate change effects (including increased fire frequency and intensity)? How will future hydrological regimes alter the transport dynamics of wood? Answering such questions will require an array of research approaches that include short-term studies, long-term investigations, remote sensing, simulation modeling, historical reconstruction, and meta-analyses of global information.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in H.J. Andrews Experimental Forest at https://andlter.forestry.oregonstate.edu/data/catalog/datacatalog.aspx.

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