

Occurrence of Windthrow in Forest Buffer Strips and its Effect on Small Streams in Northwest Washington

Abstract

Retaining streamside buffers has become a common way of protecting streams during timber harvest operations. Trees within forest buffers help stabilize streambanks, provide shade, and serve as a source of large woody debris. However, buffer trees are often subject to increased levels of windthrow which may impair some buffer functions. Forty (40) forest buffers bordering small, non-fish bearing streams in northwest Washington were assessed to quantify the level and in-stream effects of windthrow 1 to 3 years after clearcut harvest of adjacent timber. On average, windthrow affected 33 percent of buffer trees and ranged from 2 to 92 percent across the 40 sites. Sixty-seven percent of windthrown trees fell to the north, northeast, or northwest, while only three percent of the total fell towards the south. Large woody debris present in streams at the time of harvest was significantly larger than debris recruited as a result of buffer windthrow (t-test; $p < 0.01$). Windthrow increased total in-stream large woody debris piece counts by 52 percent. Seventy-five percent of in-stream large woody debris pieces recruited to streams post-harvest were suspended above the bankfull channel while four percent stored sediment. Seventeen percent of uprooted trees delivered sediment to stream channels. The average volume input was 0.16 cubic meters per uprooted tree and 0.48 cubic meters per 100 meters of stream channel at 39 sites where mass wasting did not occur. At most sites, the volume of sediment input to streams was small relative to the amount stored behind obstructions. Large woody debris was the primary component of 93 percent of in-stream obstructions which stored sediment.

Introduction

Tree mortality resulting from windthrow (uprooting and stem breakage) has been a concern to forest land managers in the Pacific Northwest for most of this century. From a timber production perspective, windthrown trees represent an economic loss. These trees lose commercial value rapidly and salvage operations are often costly. Additionally, if not salvaged, insects attracted to the dead trees can spread into surrounding timber. From a broader ecological perspective, windthrow is a natural occurrence, and downed trees contribute to forest and stream productivity.

Since the 1970s, the establishment of forest buffers has increasingly become a way of protecting streams during timber harvest operations. A common rationale for retaining streamside buffers is the assumption that they can provide many of the same functions as an intact forest. However, trees within buffers are subject to increased wind exposure and significant amounts of windthrow can impair some buffer functions. The net effect of windthrow on streams is often debated from water quality, fish habitat, channel morphology and legal liability perspectives.

State and private forest land managers in northwest Washington have established buffers which

exceed state Forest Practice rules on many small, non-fish bearing streams during the past several years. Instances of severe windthrow in these buffers have caused managers to question the practice of retaining "non-required" buffers. This study was undertaken to develop quantitative information regarding the fate and function of second-growth forest buffers retained along small, non-fish-bearing streams.

Published studies dating from the 1950s document a wide array of site, tree and forest stand characteristics that influence windthrow occurrence in Pacific Northwest forests. Regrettably, data are lacking to support the cause-and-effect relationships reported by many of those studies (Rollerson 1982). Early windthrow studies in Washington and Oregon focused on mortality along clearcut harvest boundaries and offered recommendations for cutting-line placement to reduce windthrow (Ruth and Yoder 1953; Gratkowski 1956; Steinbrenner and Gessel 1956). Research emphasis on windthrow shifted to streamside buffers in the 1970s as buffers became more common on public and private forest lands (Moore 1977; Hobbs and Halbach 1981; Steinblums et al. 1984; Andrus and Froehlich 1988; Sherwood 1993; Timber, Fish and Wildlife 1994; Mobbs and Jones 1995).

Streamside trees can exert significant influence on channel morphology and fluvial processes in small, low-order streams of the Pacific Northwest (Naiman et al. 1992). Standing trees and/or their root systems help retard streambank erosion and maintain stability of stream-adjacent hillslopes (Sullivan et al. 1987). Fallen trees and limbs supply in-stream woody debris which helps store sediment, dissipate streamflow energy, and create channel complexity. Despite these positive effects of woody debris on channel morphology, our understanding of the role of riparian and stream-adjacent forests in supplying wood has developed only recently (Bisson et al. 1987).

In this study, we characterized tree condition, large woody debris function, and stream sediment input and storage within forty (40) streamside buffers and associated non-fish bearing streams 1 to 3 years following clearcut harvest of adjacent second-growth timber. The objectives of this study were to:

- 1) quantify the amount and type of tree windthrow by species;
- 2) assess the abundance and function of in-stream large woody debris;
- 3) quantify the volume of in-stream sediment stored in discrete accumulations or wedges and the volume of sediment delivered to stream channels from uprooted trees.

Methods

Site Selection

State and private forest land managers were asked to identify potential study buffers adjacent to small streams on the lower, west slope of the North Cascades within the Stillaguamish, Skagit and Nooksack river basins of northwest Washington. From these potential sites, we randomly selected 40 buffers that met the following criteria:

- 1) non-fish bearing stream >1 meter average width;
- 2) buffer had a continuous, 180 meter or longer reach within the harvest unit;
- 3) clearcut harvest of adjacent timber occurred during the previous three years;
- 4) buffer trees were retained on both sides of the stream.

While the large majority of buffers had no removal of live trees, harvest of selected larger conifer trees did occur at three sites. The buffers were typical of merchantable, second-growth forest stands in northwest Washington, ranging in age from 40 to 60 years.

Inventory Procedure

Field work was completed during the summer of 1996. Data were collected within a 150 meter reach randomly located within each buffer. Total buffer length rarely exceeded 300 meters, thus the study reach usually included at least half of the total buffer length ($\geq 50\%$ sample).

Each study reach was divided into 15 meter segments. Channel gradient was measured for each segment; bankfull channel width, buffer width (slope distance), and adjacent hillslope gradients were measured at each segment node (11 locations). Buffer width and hillslope gradients were measured perpendicular to stream orientation. The "forming structure" associated with each in-stream sediment wedge was determined and stored sediment volume was estimated based on surface area and step height. Four classes of forming structures were identified: (1) pre-harvest large woody debris, (2) post-harvest large woody debris, (3) combination of pre- and post-harvest large woody debris, or (4) bedrock and/or boulder.

In-stream large woody debris >10 centimeters in diameter and >1.5 meters in length was tallied. Hydraulic function (sediment storage, bank protection, bank erosion, channel roughness, or bridging) and time-of-entry (pre- or post-harvest) was recorded for each piece lying within the vertical projection of the bankfull channel. Woody debris pieces outside this zone (i.e., on adjacent hillslopes) were not included in the inventory. Post-harvest debris pieces were differentiated from pre-harvest pieces based primarily on physical condition. It was assumed that pieces in more advanced stages of decay had been recruited to the channel prior to harvesting, while pieces with intact bark and/or foliage were of post-harvest origin (i.e., 1 to 3 years since time of recruitment). In addition, the degree of embeddedness exhibited by a particular piece was often used as an indicator of recruitment timing.

All standing, uprooted, and broken trees 15 centimeters diameter at breast height (DBH) and larger were inventoried. Downed trees that

appeared to result from windthrow prior to timber harvest were not inventoried. Such trees were typically in a more advanced state of decay as evidenced by loose or missing bark, and loss of branches and/or foliage. Tree condition, (standing, uprooted, or broken), diameter at breast height (DBH), distance from channel and where applicable, direction of fall, was measured. The area downslope of each uprooted tree was examined for evidence of sediment delivery to the stream channel. Where sediment delivery occurred, the volume was estimated based on surface area and depth of exposed root mass and evidence of soil movement to the channel.

Results

Site Characteristics

Most study streams exhibited morphologies typical of step-pool or cascade channel types as described by Montgomery and Buffington (1993). Streams were generally small, averaging less than 3 meters in bankfull width (Table 1). Channel gradients varied considerably and averaged 24 percent (Table 1). The outer edges of buffers often corresponded with distinct topographic slope breaks. Total buffer widths (both sides of stream) averaged 26 meters while hillslope gradients averaged 39 percent (Table 1). Sites with lower gradient channels and adjacent hillslopes were usually located in relatively wide valley bottoms while sites with steeper channels and adjacent hillslopes tended to be at higher elevations in midslope topographic positions.

The number of trees inventoried within buffer sites ranged from 60 to 537. Variations in the number of trees inventoried were attributable to differences in buffer width and stand density between sites. Stand densities prior to harvest av-

eraged 507 trees/hectare or 47.4 m² basal area/hectare (Table 1). Conifer species comprised at least 75 percent of stand density (number of trees and basal area) at 19 of the 40 sites and 90 percent or more at 14 sites. Tree DBH averaged 32.9 centimeters (Table 1).

The most common species was western hemlock (*Tsuga heterophylla*), which accounted for 33 percent of all trees inventoried. Western redcedar (*Thuja plicata*), red alder (*Alnus rubra*), and Douglas-fir (*Pseudotsuga menziesii*) accounted for 22 percent, 20 percent, and 10 percent of all trees, respectively. Bigleaf maple (*Acer macrophyllum*), Pacific silver fir (*Abies amabilis*), Alaska yellow cedar (*Chamaecyparis nootkatensis*), and black cottonwood (*Populus trichocarpa*) comprised the remaining 15 percent of trees inventoried.

Windthrow

Windthrow averaged 33 percent of stand density across the 40 sites (Figure 1). This was true regardless of whether windthrow was calculated as a proportion of total stems (trees/ha) or as a proportion of total basal area (m²/ha). Uprooting was the more common form of windthrow, averaging 27 percent of stand density while breakage accounted for the remaining six percent (Figure 1). One-third or less of the trees were windthrown at 24 sites while more than two-thirds of the trees were windthrown at three sites.

The level of windthrow varied among tree species. Pacific silver fir and western hemlock experienced the highest levels of windthrow at 37.3 and 36.0 percent of total stems, respectively. Bigleaf maple was least subject to windthrow, with 7.5 percent of trees being uprooted or broken. Windthrow occurred at intermediate levels for red

TABLE 1. Characteristics of 40 forest buffers and associated non-fish-bearing streams in northwest Washington: channel width (average channel width), buffer width (average buffer width on both sides of stream), channel gradient (average channel gradient), hillslope gradient (average hillslope gradient, both sides of stream), stand density (stand density, expressed as trees/hectare and m² basal area/ha; includes standing, uprooted, and broken trees), and stand diameter at breast height (average diameter, includes standing, uprooted and broken trees).

	Channel Width (m)	Buffer Width (m)	Channel Gradient (%)	Hillslope Gradient (%)	Density (trees/ha)	Stand Basal Area (m ² /ha)	DBH (cm)
Mean	2.7	26.3	24	39	484	47.4	32.9
Min	1.4	8.5	1	3	261	20.0	24.1
Max	5.7	64.9	63	75	995	87.3	50.0
S.D.	1.0	13.9	15	18	160	13.0	5.2

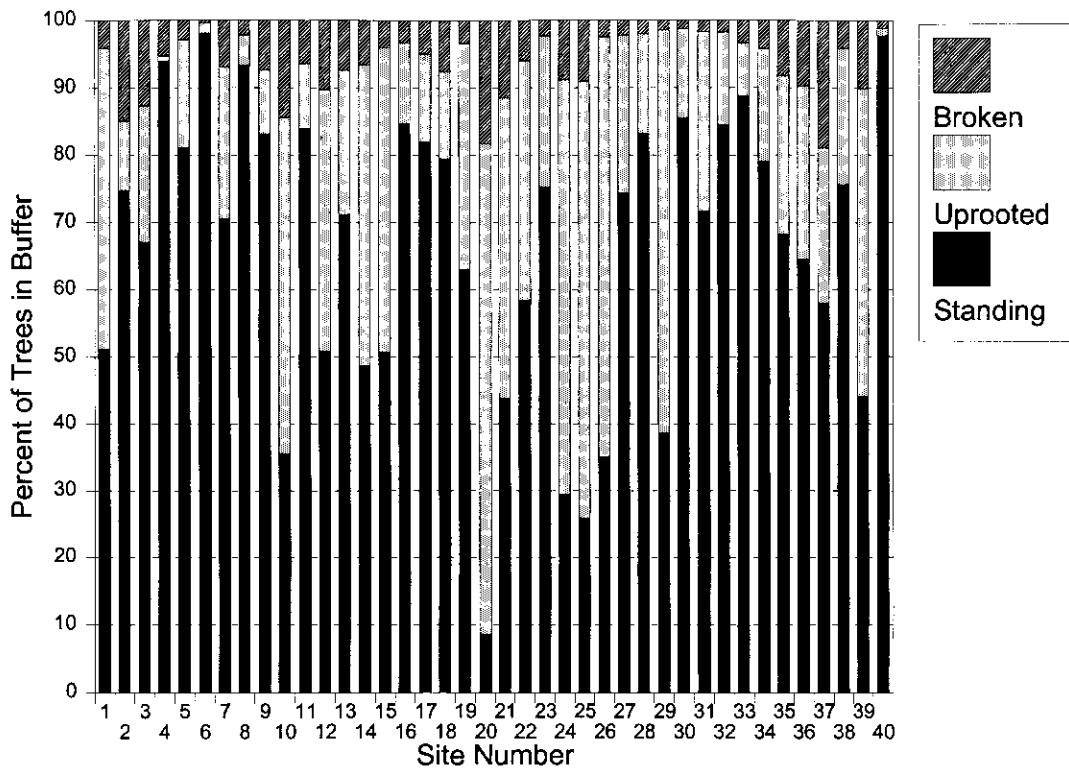


Figure 1. Proportion of standing, uprooted, and broken trees in 40 forest buffers in northwest Washington (each bar represents one site).

alder (17.2 percent), Douglas-fir (20.2 percent), and western redcedar (21.8 percent). Relatively high levels of windthrow for Pacific silver fir and western hemlock were documented in both mixed species stands as well as stands dominated by these species.

Average diameters of windthrown trees were significantly greater than standing trees for four of the six most common species ($p < 0.01$, Table 2). Windthrown western redcedar, red alder, Douglas-fir, and Pacific silver fir tended to be larger than standing trees of the same species while no difference between windthrown and standing trees existed for western hemlock and bigleaf maple.

The direction of fall of windthrown trees was strongly influenced by prevailing southerly winds. While 67 percent of all windthrown trees fell to the north, northeast, or northwest, only three percent of the total fell towards the south (Figure 2). This pattern seems to be independent of stream/buffer orientation since the 40 sites were fairly evenly distributed with respect to the four cardi-

nal directions (10 sites were oriented north-south, 8 were oriented northeast-southwest, 10 were oriented east-west, and 12 were oriented northwest-southeast).

In-Stream Large Woody Debris

Approximately one-third of all in-stream large woody debris pieces entered the stream following adjacent clearcut harvest. The proportion of post-harvest debris within the bankfull channel ranged from 2 to 77 percent of total pieces across the 40 sites. Post-harvest large woody debris comprised 25 percent of total woody debris pieces at 16 sites and 50 percent at seven sites. Piece frequencies averaged 0.66 pieces/meter (range = 0.05 to 1.34 pieces/meter) while debris volumes averaged 0.050 m^3/m^2 (range = 0.004 to 0.107 m^3/m^2).

In-stream large woody debris diameters averaged 28 centimeters (range = 21 to 37 centimeters). Pre-harvest debris was significantly larger than post-harvest debris when comparing mean

TABLE 2. Comparison of mean diameter at breast height (cm) and Standard Deviation (SD) of standing and windthrown trees and mean diameter (cm) of in-channel large woody debris deposited pre- and post-harvest in 40 forest buffers associated with non-fish-bearing streams in northwest Washington.

Species	Standing Trees		Windthrown Trees		P-value ¹
	Diam.	SD	Diam.	SD	
Bigleaf maple	32.5	(8.6)	32.3	(3.6)	0.450
Douglas-fir	38.9	(11.4)	42.2	(7.4)	<0.001
Red alder	33.0	(12.2)	34.8	(8.1)	<0.001
Western redcedar	29.2	(13.5)	30.7	(7.9)	0.003
Pacific silver fir	28.4	(4.6)	33.8	(4.6)	<0.001
Western hemlock	30.2	(13.7)	30.0	(11.2)	0.114
Large woody debris	30.0	(20.8)	24.9	(13.7)	<0.001

¹P-values for mean tree diameters were based on Mann-Whitney rank sum tests and P-values for large woody debris diameters were based on a Student's t-test.

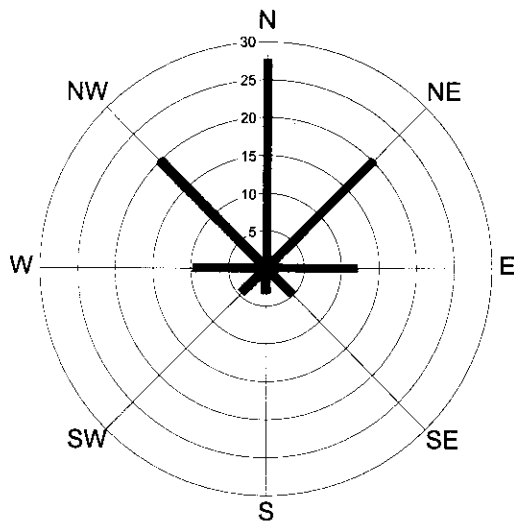


Figure 2. Percent of windthrown (uprooted and broken) trees falling in a given direction. Data is from 40 forest buffers in northwest Washington (n = 2,288).

piece diameters ($p < 0.01$, Table 2). Pre-harvest debris averaged 30 centimeters in diameter while debris of post-harvest origin averaged 25 centimeters in diameter. Forty percent of pre-harvest debris pieces were larger than 30 centimeters in diameter while only 28 percent of post-harvest pieces fell into this category. Seven percent of pre-harvest debris and less than 2 percent of post-harvest debris was larger than 60 centimeters in diameter.

Approximately 66 percent of all large woody debris pieces were located within the bankfull streamflow zone; channel roughness was the primary function associated with 55 percent of these

pieces while 32 percent stored sediment. Thirty-four percent of all woody debris pieces were suspended above the bankfull streamflow zone. While these pieces currently exert no direct influence on fluvial processes, they may become incorporated into the channel at a later date.

Figure 3 illustrates the function class distribution for both pre- and post-harvest large woody debris pieces. Eighty-five percent of pre-harvest debris pieces were located within the bankfull flow zone while 15 percent bridged the channel (Figure 3a). Twenty-eight percent of large woody debris pieces that entered streams post-harvest had a direct influence on channel processes (Figure 3b). Most post-harvest woody debris pieces bridged the stream channel (73 percent); post-harvest pieces accounted for 72 percent of all large woody debris pieces in this function class (984 of 1,364 pieces).

Sediment Storage

An average of 3.8 sediment wedges/100 meters of stream channel was recorded across the 40 sites. Seven sites had no wedge-associated storage within the study reach while 25 sites had between 0.5 and 25 m^3 of sediment stored in wedges (Figure 4). Average wedge volume was less than 3.0 m^3 for 28 of the 33 sites where wedges were present.

Large woody debris dams were the primary forming mechanism for 93 percent of all sediment wedges; the remainder were formed by bed-rock or boulder obstructions. Debris dams comprised primarily of pre-harvest large woody debris formed 76 percent of inventoried wedges while post-harvest debris dams formed 5 percent of

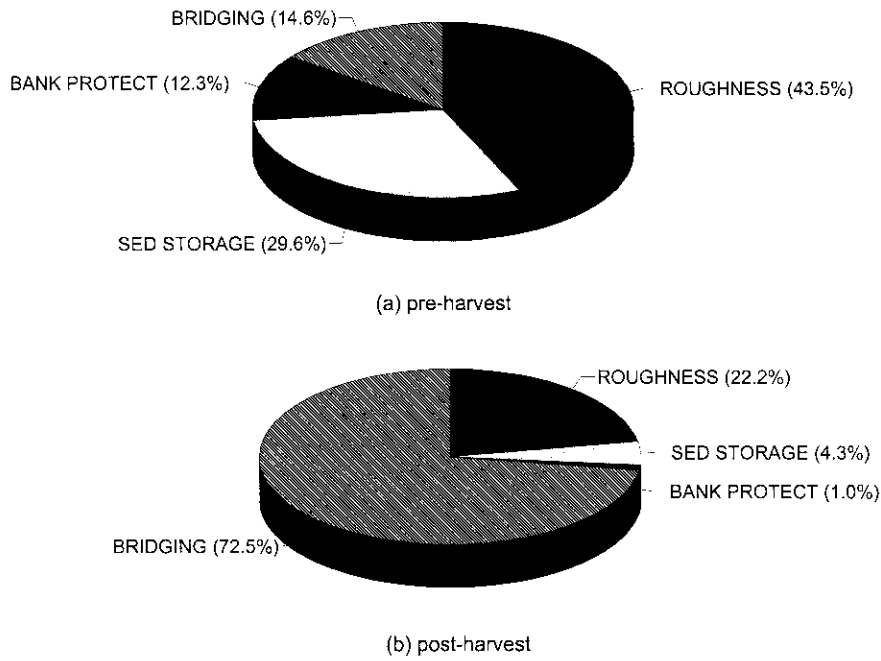


Figure 3. Function class distribution for in-stream (a) pre-harvest large woody debris (n = 2,611) and (b) post-harvest large woody debris (n = 1,357) associated with 40 non-fish bearing streams in northwest Washington.

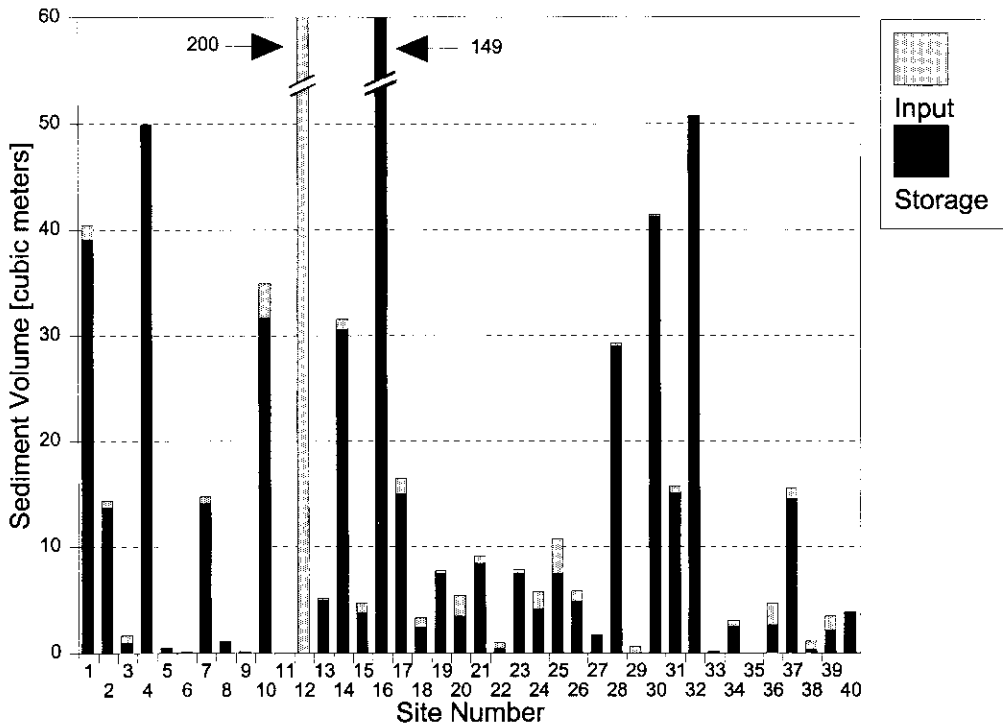


Figure 4. Sediment input and storage within 40 non-fish bearing streams in northwest Washington. Each bar represents one 150-meter stream reach. Sediment input is associated with uprooted buffer trees; sediment storage is associated with in-stream wedges created by obstructions or "dams".

wedges. Debris dams usually consisted of several pieces of woody debris anchored by larger key pieces of wood, boulders or bedrock. In many cases, the accumulated debris served to increase the height of the debris dam, thereby increasing its storage capacity. Debris smaller than our minimum piece size, and not included in the inventory, comprised a significant portion of some structures; debris dams composed wholly of such small debris also stored significant sediment volumes.

Sediment Delivery

Seventeen percent of uprooted trees delivered at least some sediment to stream channels. No sediment delivery occurred at three sites, <1 m³ was delivered at 27 sites, between 1 and 2 m³ was delivered at 8 sites, and >2 m³ was delivered at two sites (Figure 4). A disproportionate amount of the total sediment volume delivered at all sites resulted from uprooting at a single site. A mass wasting event, probably triggered by uprooting of several large trees, delivered an estimated 200 m³ of material to the channel (Figure 4). This site was characterized by steep channel-adjacent slopes comprised of deep, unconsolidated glacial outwash materials. This was the only site with this combination of geology and landform. Excluding sediment delivery at this site, inputs attributable to uprooted trees averaged 0.48 m³ per 100 meters of stream channel.

Most windthrow-related sediment delivery to streams was associated with trees located within 3 meters of the channel edge. Eighty-five percent of the sediment delivered to stream channels at 39 of the 40 sites originated from within

that zone (the mass wasting site was not included as its delivered volume exceeded the total of all other sites). Uprooted trees that fell toward or across the stream usually did not deliver sediment because the exposed portion of the rootwad faced away from the stream. Sediment inputs originating beyond 3 meters usually reached the channel as a result of trees sliding or rolling down a steep slope. However, in most cases, the rootwads of buffer trees did not move downslope after being uprooted.

At 23 of the 40 sites, sediment stored in wedges was approximately 10 times greater than the volume delivered to stream channels as a result of uprooting (Figure 4). Where delivery equaled or exceeded storage, channel gradients and/or valley confinement were generally not conducive to the formation of sediment wedges. High-gradient channels dominated by bedrock often had little capacity for sediment retention. Low gradient, unconfined channels contained large volumes of stored sediment, but most sediment was not stored in distinct wedges that met our inventory criteria. Sediment storage in these cases often occurred on adjacent floodplain landforms.

Discussion

Windthrow

In general, we found higher levels of windthrow than has been reported elsewhere in the Pacific Northwest (Table 3). Only one study, Steinblums (1978), reported average windthrow levels similar to those found by this study. The relatively high levels of windthrow found may result from

TABLE 3. Summary of reported buffer strip windthrow values in the Pacific Northwest.

Study	Location	# Sites	Buffer Age (years)	Windthrow ¹ Range(%)	Mean(%)
This study	northwest WA	40	1-3	2-92 ²	33 ^{2,5}
Mobbs and Jones (1995)	southwest WA	90	1	0-100 ²	5 ²
TFW (1994)	Washington	91	3-4	0-80 ²	10 ²
Sherwood (1993)	western OR	16	15-29	0-65 ^{2,4}	12 ^{2,4}
Andrus and Froehlich (1988)	western OR	30	1-6	0-72 ²	22 ³
Hobbs and Halbach (1981)	western WA	37	2-5	0-17 ¹	5 ²
Steinblums (1978)	western OR	40	1-15	0-78 ⁴	29 ³

¹In some cases, windthrow includes both uprooted and broken trees, while in others, only uprooted trees are included.

²expressed as a percent of stand stem density (trees/ha).

³expressed as a percent of stand basal area (m²/ha).

⁴represents windthrow that occurred over the period 1977-1990; uses Steinblums (1978) reported post-windthrow volumes as a basis for estimated windthrow.

soil, topographic, and stand characteristics unique to the North Cascades region.

Relatively recent glaciation in the North Cascades (10,000 years before present) has shaped large-scale landforms and influenced soil characteristics in ways that may influence windthrow. The typically broad, glaciated valleys and hillslopes often offer little topographic protection from winds. Buffers on small streams are commonly associated with narrowly incised channels that drain broad, exposed hillslopes. Other regions of the Pacific Northwest with highly dissected drainages may be less susceptible to windthrow due to greater protection afforded by local topography. Furthermore, soils in the region are generally shallow (< 1 meter) and underlain by compacted glacial till or bedrock which restricts root penetration and anchoring. A perched water table typically persists throughout the wet season where drainage is impeded. Sites with shallow, wet soils are typically more subject to windthrow (Stathers et al., 1994).

The tree species composition of buffers may also influence windthrow occurrence. Pacific silver fir and western hemlock comprised over a third of all trees tallied at the 40 sites and were most susceptible to windthrow. Studies which reported relatively low levels of windthrow examined sites generally dominated by deciduous tree species such as red alder (Mobbs and Jones 1995; Timber, Fish and Wildlife 1994; Hobbs and Halbach 1981), which tend to be more windfirm than most species.

Site conditions documented in this study illustrate the influence of prevailing southerly winds on tree fall direction. Such information may suggest that buffer orientation could influence the degree of windthrow at a given site. That is, one might expect buffers oriented perpendicular to the direction of prevailing winds would experience higher levels of windthrow than those oriented parallel to prevailing wind direction. In this study, we documented a wide range of windthrow levels and tree fall directions. However, we found no evidence to indicate that buffer orientation influenced windthrow levels. It is likely that the level of windthrow occurrence at a given site is a complex interaction of a range of factors which vary in their degree of influence from site to site.

In-Channel Large Woody Debris

Buffer windthrow increased the number of in-channel large woody debris pieces by 34 percent

across the 40 sites within one to three years after harvest. Such short-term increases in wood loading suggests that buffer windthrow is a significant mechanism by which debris is recruited to streams soon after harvest. Furthermore, tree fall patterns we documented suggest that woody debris recruitment from forest buffers is non-random, with trees tending to fall towards the north. For streams with east-west orientations, this suggests that much of the debris recruitment occurring within a few years post-harvest will originate from the south side of the stream.

Much post-harvest debris recruited to channels was suspended over the stream and will do little to influence channel processes in the near-term. These pieces must undergo a secondary recruitment phase where they break apart and enter the bankfull flow zone. The time between the initial windthrow and this secondary phase will vary depending on the species, size, and condition of wood pieces. Secondary recruitment of smaller hardwoods is likely to occur in a matter of a few years while larger conifers may remain suspended for decades.

The role of woody debris in retaining sediment in small headwater stream channels of the northwest has been documented previously (O'Connor and Harr 1994; Potts and Anderson 1990; Megahan 1982). Potts and Anderson (1990) found that organic matter accounted for over 60 percent of total sediment storage within eight reaches of first to third order channels in western Montana. Similarly, Megahan (1982) reported that organic material formed 76 percent of channel obstructions associated with sediment storage in seven small drainages in the Idaho batholith. Removal of this material via salvage logging or stream cleanout would likely destabilize the channel (Bilby 1984) and increase sediment export from the system (O'Connor and Harr 1994). Thus, buffers may provide a long-term source of large woody debris which helps create and maintain debris loads and reduce sediment yields. However, large woody debris recruited as a result of windthrow (post-harvest debris) was significantly smaller in diameter than debris recruited prior to buffer establishment (pre-harvest debris). A portion of the pre-harvest debris load consisted of larger pieces recruited from the original forest. Smaller debris generally has a shorter residence time and may be less effective at creating and maintaining sediment storage sites compared to larger pieces.

Sediment Delivery

In most cases, the volume of sediment delivered to stream channels as a result of post-harvest windthrow was relatively small. Sediment delivery at all sites averaged 1.43 m³/uprooted tree. However, the average was only 0.16 m³/uprooted tree at 39 of the 40 sites where mass wasting was not associated with uprooted trees. Except under the unusual physical conditions present at this single site, windthrow did not accelerate mass wasting. Andrus and Froehlich (1988) reported an average delivery of 0.87 m³/uprooted tree for windthrow in the Oregon Coast Range. They concluded that the volume of sediment delivered to streams was usually small compared to overall watershed sediment yield and that uprooted trees did not accelerate mass wasting. Increases in sediment inputs attributable to windthrow may be offset by sediment storage sites created by recruited woody debris; however, we found that relatively few post-harvest debris pieces were currently storing sediment (Figure 3b).

Most windthrow-generated sediment delivery originated from trees rooted in the streambank. This zone generally extends outward 3 meters from the channel edge and accounted for approximately 85 percent of windthrow-generated sediment delivery. While harvest of trees in this zone might reduce sediment input to streams, other buffer functions such as rooting strength, woody debris recruitment, and shade would be reduced or eliminated.

Conclusions

The magnitude of windthrow in buffers bordering small, non-fish bearing streams in northwest Washington is highly variable. Even so, observed windthrow levels were generally higher than those reported in studies for other areas in the Pacific Northwest.

In a managed forest landscape, buffer windthrow is likely the most significant mechanism by which large woody debris is recruited to

stream channels. Such debris is an important structural component in small headwater streams where it forms debris jams which trap and store sediment. However, for narrow, confined stream channels, windthrown trees are commonly suspended above the channel, providing little immediate influence on channel processes and sediment routing.

Generally, results of this study indicate windthrow is not a significant source of sediment delivery to stream channels. In addition, volumes of sediment delivered to streams as a result of windthrow were small relative to the amount stored within the channel. A notable exception occurred at a single site where uprooted trees accelerated mass wasting and delivered large volumes of sediment to the channel. This was the only site where the forest buffer developed in deep, unconsolidated glacial outwash materials.

Forest buffers are often established to maintain a range of ecosystem functions; windthrow may compromise some of these functions (e.g., shade, water quality, streambank stability) while at the same time enhancing others (e.g., large woody debris recruitment, sediment storage). The extent to which these functions are affected will depend on the magnitude and spatial and temporal occurrence of windthrow.

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