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SUSPENDED SEDIMENT DYNAMICS IN SMALL FOREST STREAMS OF THE PACIFIC NORTHWEST[1]

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ABSTRACT: This paper reviews suspended sediment sources and transport in small forest streams in the Pacific Northwest region of North America, particularly in relation to riparian management. Mass movements, roading and yarding practices, and burning can increase the supply of suspended sediment. Sediment yields recovered to pre-harvest levels within one to six years in several paired catchment studies. However, delayed mass movements related to roads and harvesting may produce elevated suspended sediment yield one or more decades after logging. There is mixed evidence for the role of streamside tree throw in riparian buffers in supplying sediment to streams. Harvesting within the riparian zone may not increase suspended sediment yield if near stream soils are not disturbed. Key knowledge gaps relate to the relative roles of increased transport capacity versus sediment supply, the dynamics of fine sediment penetration into bed sediments, and the effects of forest harvesting on suspended sediment at different scales. Future research should involve nested catchments to examine suspended sediment response to forest practices at multiple spatial scales, in combination with process-based field studies.

(KEY TERMS: suspended sediment; small forest streams; forest harvesting; forest roads; riparian zone; riparian buffer; headwater streams; Pacific Northwest.)

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INTRODUCTION

Suspended load comprises the major portion of total sediment load in most river systems (Dietrich and Dunne, 1978; Dunne and Leopold, 1978) and has important influences on physical and biological processes in small streams. Increased suspended sediment load or concentration due to land use changes has long been one of the dominant concerns in stream and watershed management (Haupt and Kidd, 1965; Corbett *et al.*, 1978; Campbell and Doeg, 1989). Soil disturbance can increase fine sediment supply to channels, while changes in hydrologic regimes can alter storm flow response and thus increase sediment transport. In particular, forest practices such as road building and log skidding have the potential to elevate suspended sediment supply and concentrations in stream water (e.g., Brown and Krygier, 1971; Beschta, 1978).

Increased suspended sediment concentrations can be detrimental for stream biota and water users. High levels of suspended sediment can cause direct damage to fish gills, interfere with sight feeding, and cause siltation of bed materials, which reduces permeability and thus the movement of oxygenated water into redds, which in turn can hamper incubation (Lisle, 1989; Newcombe and MacDonald, 1991). Fine sediment accumulation in channel substrate reduces the complexity of habitat structure and availability of oxygen for benthic organisms (Rosenberg and Wiens, 1978; Murphy and Hall, 1981, Campbell and Doeg, 1989). Suspended sediment can impair drinking water quality directly, by exceeding guidelines for turbidity, as well as indirectly, by reducing the effectiveness of chlorination for eliminating pathogens and increasing treatment cost.

This paper reviews published information on the dynamics of suspended sediment relevant to forest harvesting and riparian management around small

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stream channels, with specific attention to the Pacific Northwest of North America. The paper focuses as much as possible on small streams (catchment area less than 100 ha or stream width less than 2 to 3 m) within the Pacific Northwest. Since small streams are typically headmost and upland channels, relevant processes on hillslopes, in zero-order basins (Tsukamoto *et al.*, 1982), and in riparian zones are also discussed. For some topics, such as sediment generation from forest roads, the literature is vast, and relevant examples are cited.

This paper focuses on issues related to water quality and aquatic habitat rather than geomorphic processes, which are addressed in three companion papers (Benda *et al.*, 2005; Hassan *et al.*, 2005a,b). In particular, the following questions related to forest and riparian management are addressed: (1) What is the role of harvesting induced changes in hydrology compared to changes in sediment supply? (2) How quickly do post-harvest changes in suspended sediment transport recover to pre-harvest levels? (3) What is the efficiency of riparian buffers for protecting against increases in suspended sediment yield? (4) Do the effects of forest harvesting on suspended sediment vary with basin scale? (5) To what extent do methodological difficulties (e.g., experimental design) impede the understanding of the effects of harvesting on suspended sediment regimes? and (6) What are the significant knowledge gaps that require further research? Although the focus is on suspended sediment dynamics in small streams of the Pacific Northwest, reference is made to relevant studies that have been conducted in larger streams (compared to the definition above) and to studies conducted in the other regions of North America and elsewhere, in cases in which they provide useful insights that are not available from local studies on small streams.

DEFINITIONS AND MEASUREMENT

Sediment in a stream is classified as wash load and bed material load. Wash load is relatively fine material that moves rapidly in suspension through a reach without being deposited in the main channel, while bed material load is larger material that occasionally settles out and is stored on the bed. Transport of bed material can occur as suspended load or bed load (Knighton, 1998). For most streams, sediment particles carried in suspension are fine sand and silt sized and clay sized particles – that is, they have diameters less than about 0.2 mm. Particles that are too large to be carried in suspension are rolled, pushed, or saltate along the bed and typically comprise material greater than 2 mm in diameter. Depending on flow magnitude, medium and coarse sand (0.2 to 2 mm) may move either in suspension or as bed load.

Fine sediment in the water column can be quantitatively expressed as either suspended sediment concentration (SSC), typically in milligrams of sediment per liter of water, or as turbidity (e.g., in Nephelometric Turbidity Units). Suspended sediment concentration is measured by filtering water samples to extract the sediment. Turbidity sensors measure the degree to which light transmission is impeded by suspended particles. A statistical relation between SSC and turbidity can be derived, but the relation depends on sediment mineralogy, particle size distribution, and availability of particulate organic matter, which can vary through time, even at a single location (Pfannkuche and Schmidt, 2003). It also depends on turbidity detection principles (i.e., whether light is reflected, refracted, or transmitted) and wavelength. Therefore, relations between SSC and turbidity can be complex and highly variable both within and among storms. The SSC can be estimated from occasional water samples by deriving empirical relations with turbidity, stage, or discharge, or by linear interpolation with time (Lewis *et al.*, 2001). Correlations with discharge (Q) are commonly used, and the empirical SSC-Q relation is often called the suspended sediment rating curve. The most commonly used model is a power law function of the form

$$\mathrm{SSC} = \mathrm{a}\mathrm{Q}^{\mathrm{b}} \tag{1}$$

where SSC is the suspended sediment concentration (g/m^3), Q is flow (m^3/s), and a and b are empirical coefficients.

Suspended sediment yield is the total mass of suspended sediment that leaves a drainage basin in a given time and can be estimated by integrating the suspended sediment transport rate over time as

$$\mathrm{SSY} = \int_{\tau} \mathrm{Q(t)SSC(t)}\,\mathrm{dt} \tag{2}$$

where SSY is the suspended sediment yield (g); τ is the time interval of interest; Q(t) is the stream discharge (m^3/s) at time t; and SSC(t) is the suspended sediment concentration (g/m^3) at time t. Suspended sediment yields have been computed for storm (Lewis *et al.*, 2001), monthly (Beschta, 1978), and annual time scales (Harris, 1977). Values are commonly reported as specific suspended sediment yield, computed by dividing SSY by the catchment area.

Sampling protocols for suspended sediment tend to overrepresent low flows and sediment concentrations (Thomas, 1988; Thomas and Lewis, 1993). Thomas (1985) introduced a sampling scheme for enhancing the probability of sampling during high flow to generate rating curves that more effectively span the range of suspended sediment concentrations and discharges, resulting in more accurate estimates of suspended sediment yield.

An alternative approach is to measure total sediment yield (suspended and bed load) through the construction of sediment trapping ponds at the catchment outlet (e.g., Leaf, 1970; Verstraeten and Poesen, 2002). Although such measures do not allow separate determination of suspended and bed load transport, they should provide an index of year-to-year variability in suspended sediment load. However, because trap efficiency of ponds may differ for sizes of sediment, depending on their size and throughflow velocity, calibration for trap efficiency and bulk density of sediment may be necessary (Verstraeten and Poesen, 2002).

SOURCES OF SUSPENDED SEDIMENT

Suspended sediment in small streams is supplied from sources both external and internal to the stream channel. External sources include bank erosion, mass movement, roads and trails, and surface erosion on slopes (e.g., rain splash, sheet wash, freeze/thaw, and animal activity); internal sources include material stored within the channel system from perennial and ephemeral reaches (Table 1). Bank erosion is an important source of fine sediment where floodplains exist adjacent to a stream channel. However, bank erosion rates in forest headwater streams are likely to be low relative to those in larger streams and hence will not be discussed here (for more information on bank erosion see Hassan *et al.,* 2005a). Size distributions, color, and mineralogy of particles can often be used to identify or "fingerprint" the sources of sediment (Walling and Moorehead, 1989; Kurashige, 1994; Udelhoven *et al.,* 1997; Lenzi and Marchi, 2000). For example, Christie and Fletcher (1999) employed bed sediment geochemistry to identify logging road fill material as the dominant sediment source in logged headwater catchments in the central interior of British Columbia.

External Sources

Mass movements such as landslides and debris flows are the major external sediment sources in forested steepland regions of the Pacific Northwest (Roberts and Church, 1986; Hassan *et al.,* 2005a) (Table 1). In two Oregon studies, mass movement events increased suspended sediment yield approximately two-fold to five-fold (Beschta, 1978; Grant and Wolff, 1991). However, the delivery of fine material due to mass movements depends on the width and incision of the valley, which affect the degree of connectivity from hillslopes to channels (Roberts and Church, 1986). Suspended sediment is also delivered

TABLE 1. Sources of Suspended Sediment in Small Streams.*

	External Sources[1]
Infrequent	Landslide, debris flows, avalanche, slope failures, wind throw, earth flow
Frequent	Slope surface erosion (rain splash, sheet erosion, dry ravel, freeze/thaw), bank erosion, glacier discharge
Potential Effect of Logging	Road fill failures (mass movement), road surface, cut slope, fill, and ditch, slash burning, wind throw in riparian buffer, tree/wood death and decay, soil compaction, soil clearing by yarding
	Internal Sources[2]
Infrequent	Breakage of log jams, animal crossing, redd excavation by salmonids
Frequent	Channel substrate, sediment wedge, bank deposits (within bankfull width), headward channel extension, soil subsurface erosion (pipe flows)
Potential Effect of Logging	Changes in flow response, slash entrainment (channel roughness), in-channel storage (substrate and sediment wedge)

*Forest fire and wind throw both affect the occurrence of external suspended sediment sources.

[1] External sources are those located on hillslopes in headwaters and in the riparian zone outside the bankfull width, including zero-order basin.

[2] Internal sources are ephemeral and perennial channels.

to channels from unvegetated soil surfaces that were disturbed by past debris flows (Smith *et al.*, 1983; Commandeur, 1992). Establishment of vegetation on debris flow tracks can result in recovery of suspended sediment supply rates toward predisturbance levels (Grant and Wolff, 1991).

Soil erosion processes such as sheet erosion, rain splash, dry ravel, freeze/thaw, and animal activities are chronic sources of sediment supply. In general, the amount of suspended sediment yield due to soil erosion in forested catchments of the Pacific Northwest is low because of the protective effect of dense vegetation cover. Moreover, well developed organic surface soil horizons prevent particle detachment and transport (e.g., Roberts and Church, 1986). Infiltration excess overland flow is rarely observed in forested catchments due to the typically high infiltration capacities of forest soils (Hewlett and Hibbert, 1967; Harr, 1977; Cheng, 1988). However, depending on soil moisture conditions, saturation excess overland flow in zero-order basins and hollows may introduce additional fine sediment to headwater channels. During very wet conditions, saturation excess overland flow may allow recruitment of sediment from areas that are not consistently connected to the channel network (Rivenbark and Jackson, 2004). Dry ravel has been observed even under forest cover on slopes in the H.J. Andrews Experimental Forest, Oregon (Swanson *et al.*, 1982). Although soil disturbance due to snow avalanches is a potential source of suspended sediment, no studies appear to have quantified it.

Glaciolacustrine and glaciomarine sediments are common in many regions in the Pacific Northwest, particularly in coastal regions of British Columbia and in glacially sculpted valleys (Evans, 1982; Armstrong, 1984; Clague, 1984, 1988). These fine grained deposits are prone to surface erosion and mass failures associated with piping and gullying.

Changes in forest conditions due to forest fire, tree throw, and insect and disease outbreak modify the rates of episodic and chronic supply of suspended sediment (Agee, 1993, Benda *et al.*, 1998). For example, monthly suspended sediment yield during summer periods increased 470 percent following a 1988 forest fire in the Lamar River basin (drainage area 1,730 km^2) of Yellowstone National Park (Ewing, 1996). Forest fires may lead to erosion by dry ravel on steep slopes (Wondzell and King, 2003). In addition, heat from forest fires can create a water repellent barrier in the soil depending on the severity of heat. This barrier can decrease infiltration capacity and increase overland flow (McNabb and Swanson, 1990). Fire induced water repellency appears to be important mainly for drier forest types (Wondzell and King, 2003), likely because it takes a very hot fire on wet sites to induce hydrophobicity. However, water repellency has been observed in undisturbed soils in subalpine forests in wetter regions such as the Coast Mountains of British Columbia (Barrett and Slaymaker, 1989). Changes in hydrologic regimes (e.g., peak flow response) due to forest fire and vegetation loss may also affect suspended sediment transport by increasing the transport capacity of streams (Beschta, 1990).

Tree throw produces local soil disturbance and bank undercutting and can be caused by several processes, including wind throw and snow and ice loading, which can be particularly important in coastal areas subject to occasional heavy falls of wet, cohesive snow. Tree throw on upslope areas is unlikely to result in increased sediment delivery to a stream unless the root wad is located along an ephemeral stream channel or in a zero-order basin that can become hydrologically connected by overland flow to the channel.

Glacier fed streams have distinctive external sources of suspended sediment, including subglacial erosion and erosion of till and glaciofluvial deposits (Harbor and Warburton, 1993; Hallet *et al.*, 1996; Schiefer *et al.*, 2001; Richards and Moore, 2003). Greater suspended sediment yields are typically observed in glacier fed streams. While a detailed discussion of suspended sediment dynamics in glacier-fed streams is beyond the scope of this paper, it is important to note that suspended sediment transport in these streams can play an important role in basin-wide sediment dynamics and downstream influences, particularly in the British Columbia Coast and Columbia Mountains and the High Cascades (Slaymaker, 1987; Church and Slaymaker, 1989).

Internal Sources

Streambed materials can be important internal sources of suspended sediment. Usually, fine sediment is stored between large particles within or immediately beneath the surface layer. Partial or total mobilization of the surface layer can release large amounts of fine material stored in the subsurface layer (Jackson and Beschta, 1982; Kurashige, 1994; Hassan *et al.*, 2005a). The amount of fine sediment released varies seasonally, depending on the accumulation and exhaustion of fine sediment storage in channels and banks (Paustian and Beschta, 1979; Sidle and Campbell, 1985). In forest headwater streams, large amounts of sediment can be stored behind wood pieces and interlocked boulders (e.g., Megahan, 1982). Beschta (1979) showed that removal of wood in a third-order stream channel in the Oregon Coast Range increased the amount of suspended sediment transport over the one season of monitoring. The greatest increases in turbidity occurred in the first few storms in autumn and winter, with relatively low turbidities in late winter and spring storms, suggesting a rapid flushing of available sediment. Breakage or movement of wood may release pulses of fine sediment during storms (Grant and Wolff, 1991).

In small fish bearing streams, scouring of spawning beds by adult salmon can disrupt an armor layer and alter local bed structures. Since spawning activities often occur during the autumn high flow season, they can release fine sediment from the surface and subsurface layers of channel beds (Kondolf *et al.,* 1993; Hames *et al.,* 2000; Gottesfeld *et al.,* 2004). Animal crossing of streams (e.g., ungulates, cattle) can also generate sediment by disrupting the channel bed and causing bank erosion (Buckhouse *et al.,* 1981; Kondolf, 1993), especially in areas such as the interior of British Columbia, where free range ranching is common.

Extension of continuous flow into ephemeral channels during storm events can provide new sources of suspended sediment to downstream reaches (Figure 1). Because of differences in peak response of flow and suspended sediment transport in a zero-order basin (Section A in Figure 1) and channel (Section B in Figure 1), suspended sediment concentration at the catchment outlet may have two peaks: the first peak associated with suspended sediment from internal sources and the second related to external sources (e.g., zero-order basin). Channelized saturation excess overland flow is commonly observed in zero-order basins during high moisture conditions, typically several times per year (Sidle *et al.,* 2000). Accumulated fine sediment in zero-order basins may be transported to downstream reaches during these wet conditions when extensive saturated zones provide a hydrologic connection between zero-order basins and the perennial channel system. However, a study in the Oregon Coast Range demonstrated that ephemeral reaches acted as sediment filters, removing 60 to 80 percent of suspended sediment (1.6 to 53 mm diameter) from the water column (Dieterich and Anderson, 1998).

Suspended sediment can also be transported from subsurface flow in hillslopes and zero-order basins (Figure 1; Table 1). Ziemer (1992) observed relatively low suspended sediment concentrations in discharge from soil pipes draining three headwater swales in northern California prior to logging. After logging of two of the swales, suspended sediment transport from the pipes increased, although there was great temporal and spatial variability in the response. Terajima *et al.* (1997) found that pipe flows from a zero-order

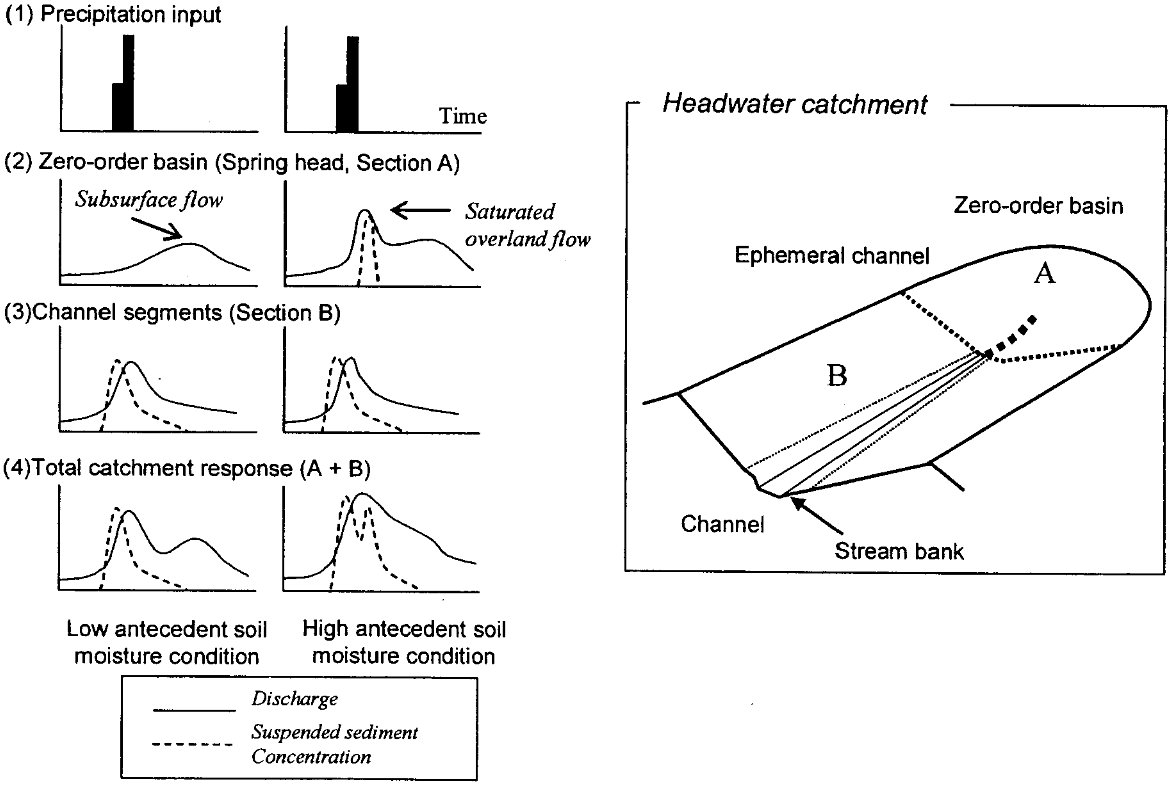

Figure 1. Hypothetical Hydrologic Response and Potential Suspended Sediment Concentration in a Headwater Catchment During Low and High Antecedent Soil Moisture Conditions (x axis shows relative time sequence; y axis shows relative magnitude).

basin contributed up to 20 percent of the total suspended yield in a first-order catchment in northern Japan. While Terajima *et al.* (1997) reported that higher SSC occurred during the rising limb of the storm hydrograph, Kurashige (1993) observed higher SSC at a headwater spring during falling limbs of storm hydrographs. Kurashige (1993) concluded that sediment generated from roads located at an upper hillslope was transported via relatively slow subsurface flows to the spring, producing a delayed peak in SSC. Onda (1994) observed that seepage erosion at a channel head induced small slope failures, thereby supplying sediment to the channel.

CHARACTERISTICS OF SUSPENDED SEDIMENT TRANSPORT

Suspended Sediment Concentration

Suspended sediment concentration depends on the interactions among the processes of flow generation, flow magnitude (transport capacity), sediment delivery from external sources, and the amount of fine sediment mobilized from internal sources. Variability in SSC can occur over a wide range of temporal scales. At the shortest time scales (seconds to minutes), it is associated with turbulent eddies. For longer temporal scales, the rate of sediment supply tends to be the limiting factor for SSC at high flows in headwater catchments. Fine sediment supply exceeds transport capacity when mass movement and slope failures occur (transport limited), whereas suspended sediment supply is normally limited compared to the transport capacity of channels (Gomi *et al.,* 2004; Nistor and Church, 2005).

Intra-event variability is primarily expressed as differences in the SSC-Q relation between the rising and falling limbs of the flow hydrograph. During rain events, the available sediment supply is often exhausted during the rising limb, so that SSC usually peaks and drops off earlier than streamflow. This process produces clockwise hysteresis in a plot of SSC against streamflow; that is, SSC tends to be higher on the rising limb than on the falling limb (Williams, 1989). Kurashige (1996) hypothesized that most fine sediment was supplied from within the channel bed substrate and that clockwise hysteresis resulted from the lifting of fine sediment from the matrix of channel substrate. A series of storms can lead to a depletion of suspended sediment supply, such that each successive storm transports less sediment than the previous storm (Paustian and Beschta, 1979). On a seasonal time scale, Beschta (1978) found that supply depletion led to lower SSC when the flow event occurred after the time of annual peak discharge.

Nistor and Church (2005) investigated suspended sediment dynamics in a steep debris flow gully on northern Vancouver Island, British Columbia. During events with flows exceeding a threshold value, SSC increased with flow. Smaller events were apparently supply limited, with SSC decreasing with discharge. Sediment supply depletion was observed between runoff events within subseasons, suggesting that significant replenishment occurred during the dry summer season and during cold spells in the wet season, possibly related to dry ravel and frost.

Hysteresis has been recorded in some snowmelt dominated catchments, with an initial flush of sediment associated with the early part of the seasonal hydrograph rise creating the highest SSC, followed by declining SSC, even if discharge remains high (Lenzi and Marchi, 2000; Henderson and Toews, 2001; Richards and Moore, 2003). However, in some catchments, each period of high snowmelt induced runoff during the spring freshet can produce similar peak levels of turbidity (Jordan, 2001), suggesting the presence of relatively large amounts of available sediment. However, these studies were in catchments greater than 5 to 10 km^2 in area, substantially larger than would be considered "headwater" catchments in the current context. Macdonald *et al.* (2003) documented clockwise hysteresis in the SSC-Q relation during spring freshets in three small catchments (drainage areas 43 to 150 ha), with SSC on the rising limb of the freshet being up to about six times greater than on the falling limb.

Several studies have attempted to accommodate hysteretic and threshold behavior in models of the relation between SSC and discharge. Sidle and Campbell (1985) modeled the suspended sediment yield in a sequence of storms and differentiated between the rising and falling hydrograph limbs within individual storms. Paustian and Beschta (1979) employed a multiple regression model including discharge (Q), cumulative discharge volume (ΣQ), and hydrograph slope (dQ/dt). Van Sickle and Beschta (1983) developed a model for SSC that addressed the temporal variation in sediment availability in and near stream channels. They modified Equation (1) by including a function representing the availability of stored sediment in locations such as bars and the channel banks, which can be accessed as flow increases and is depleted as sediment is transported out of the catchment. Parker and Troutman (1989) obtained better predictions of the load by relating annual load to annual peak flow. Kurashige (1996) incorporated suspended sediment stored in subsurface layers of channel beds in his supply based model. Moore (1984) developed a dynamic model of suspended sediment yield including availability, removal (relative to storm magnitude), and translation of suspendable solids.

Sediment Routing

Headwater streams tend to have less storage capacity than downstream alluvial reaches, where significant amounts of sediment can be stored over a range of time scales in the floodplain (riparian zones) and alluvial fans as well as bars and side channels. However, sediment can be stored, at least transiently, by settling of sediment in pools, trapping by leaf packs, as coatings of fine silt and clay on boulders, and within the framework of substrates, for example between larger particles and behind woody debris (Lisle and Hilton, 1982; Dieterich and Anderson, 1998; Richards and Moore, 2003). The presence of woody debris appears to promote retention of fine sediment (Harmon *et al.*, 1986; Duncan *et al.*, 1987). Fine sediment infiltration into bed sediments occurs in association with water infiltration, particularly in channel reaches with significant hyporheic exchange flow (Packman and MacKay, 2003; Rehg *et al.*, 2005).

An important question is whether and how frequently stored sediment is re-entrained and transported to downstream reaches. In the lower gradient, riffle pool reaches of coastal gravel bed streams, fine sediment tends to accumulate in the bed gravels during low flow periods and then be flushed during storms (Sheridan and McNeil, 1968; Scrivener and Brownlee, 1982; Bilby, 1985; Church, 1998). This flushing may be promoted by the mobilization of the armored bed surface layer. However, results from riffle pool streams may not be completely transferable to smaller "headwater" streams, where the stream may be incapable of moving the larger bed material, except during infrequent channel disturbing events. Dieterich and Anderson (1998) suggested that sediment stored in ephemeral channels may be permanently removed from the water column. On the other hand, Christie and Fletcher (1999) documented the displacement of bed material load downstream of cut blocks using sediment geochemistry in snowmelt-dominated headwater streams in the central interior of British Columbia. However, they did not explicitly focus on suspended sediment transport.

Suspended sediment may be stored over longer time frames in slow water environments, including ponds, lakes, reservoirs, and wetlands. Sediment accumulations in these environments have been used to estimate long term sediment yield in larger basins in relation to land use and climate changes (e.g., Walling, 1983; Foster and Lees, 1999), including two studies in the Pacific Northwest (Ambers, 2001; Schiefer *et al.*, 2001). In plateau watersheds in the interior of British Columbia, wetlands and ponds that are located along headwater reaches may be able to store fine sediment by vegetation trapping and settling. However, no studies appear to have examined the temporal and spatial dynamics of suspended sediment deposits in these environments or how they are influenced by forestry activities.

Sediment Yield

Table 2 summarizes specific suspended sediment yields from undisturbed small catchments in the Pacific Northwest and elsewhere. Anderson (1954) reported that generally greater suspended sediment yield (4.5 to 4,300 $t/km^2/yr$) was observed in small forested catchments (< 5 km^2) of coastal Oregon and California compared to elsewhere in the United States. Suspended sediment yield in the other western U.S. states ranged from 2.3 to 117 $t/km^2/yr$ (Patric *et al.*, 1984). Catchments dominated by sandstone generally have greater suspended sediment yield (most exceeding 50 $t/km^2/year$) compared to metamorphic and igneous geologies (Table 2). The underlying geology can influence not only the sediment yield but also the sediment size distributions. For example, Duncan and Ward (1985) found strong correlations between the percentage of sedimentary rock in watersheds and percentages of fine sand, slit, and clay particles in the channel substrate. Other controls on sediment yield include the intensity, frequency, and duration of rain events (e.g., Griffiths, 1982) and catchment morphology (e.g., McPherson, 1975). Most sediment yield studies focused on catchments larger than the ones considered to be "headwater" catchments herein. Given that larger catchments typically have greater sediment storage capacity and would be expected to have finer sediment, caution must be applied in transferring results to headwater units.

EFFECTS OF FOREST MANAGEMENT ON SUSPENDED SEDIMENT REGIMES

Sediment Generation and Delivery

Forest management practices can increase fine sediment supply though soil disturbance and accelerated landsliding (Tables 1 and 3). Redirection of hillslope flow by roads and their drainage systems can create new pathways for transporting sediment from hillslopes to channels (Wemple *et al.*, 2001). Localized increases in water table levels and pore pressures induce slope failure. Die-off and decay of tree roots

TABLE 2. Suspended Sediment Yields in Unmanaged Small Catchments.

Basin Name	Location	Area (km^2)	Elevation Range (m)	Annual Precipitation	Geology	Dominant Land Forest Type	Period of Monitoring	Annual Sediment Yield ($t/km^2/year$)	References
Bambi Creek	SE Alaska	1.54	5-614	1,670	Silurian Greywacke, Argillite	Hemlock, Sitka Spruce old growth forest	1980-1982	20.0	Sidle and Campbell (1985)
Goat Creek	Pemberton, British Columbia	0.02	–	750	Metamorphic Rocks	n/a (forested)	n/a	1.0***	Slaymaker (1987)
Central Creek	Pemberton, British Columbia	2.4	–	750	Metamorphic Rocks	n/a (forested)	n/a	5.0***	Slaymaker (1987)
Jamieson Creek	North Vancouver British Columbia	3	–	1,200	Metamorphic Rocks	n/a (forested)	n/a	5.0***	Slaymaker (1987)
WS2 (HJ Andrews)	Coastal Oregon	0.6	525-1,065	2,300	Volcaniclastic Rock	Douglas-fir	1958-1988	18	Grant and Wolff (1991)
Needle Branch	Coastal Oregon	0.75	225*	2,540	Tyee Sandstone	Douglas-fir, alder	1959-1969	53	Beschta (1978); Brown and Krygier (1971)
Deer Creek	Coastal Oregon	3.04	254*	2,540	Tyee Sandstone	Douglas-fir, alder	1959-1969	97	Beschta (1978); Brown and Krygier (1971)
Flynn Creek	Coastal Oregon	2.02	300*	2,540	Tyee Sandstone	Douglas-fir, alder	1959-1969	102	Beschta (1978); Brown and Krygier (1971)
Rock Creek	Coastal Oregon	16.2	–	3,400	Basaltic lavas intruded aphanitic basalt	Douglas-fir old growth	n/a	28	Dietrich and Dunne (1978)
Lone Tree Creek	West California	1.74	300-1,500	865	Greywacke melange	Shortleaf pine forest	1972-1974	607	Lehre (1982)
Subbasin (Johnson Gulch)	Montana	0.68	1,050-2,291	680	Quartzite, Argillite	Douglas-fir, Western larch		0.056-0.102	Anderson and Potts (1987)**
Lexen Creek	Colorado	1.24	3,002-3,538	700	Glacial till, gneiss. schist	Lodgepole pine, Spruce-fir	1957-1966	2.5***	Leaf (1970)

*Average elevation.
**Undisturbed basins were selected from the studies.
***Include both suspended and bed load sediment.
n/a = not available.

TABLE 3. Summary of the Effect of Timber Harvesting and Riparian Management on Suspended Sediment Concentrations or Yields (post logging period).

Catchment	Study Location	Area (km^2)	Geology	Harvesting Treatment	Roads	Riparian Treatment	Response Variable	Post-Logging SS Yield ($t/km^2/yr$)	Treatment Effect	Recovery	Reference	Comments
Fool Creek	Fraser Experimental Forest, Colorado	2.89	Glacial till, gneiss, schist	40% of basin harvested in strip cuts; logs skidded by horses to spur roads	1.8 km/km^2; 5% of catchment area cleared	No harvest within 27 m of stream	Annual sediment yield measured at a settling pond	n/a	n/a	n/a	Leaf (1970)	No pre-impact data
Deadhorse Creek (North Fork)	Fraser Experimental Forest, Colorado	0.41	Glacial till, gneiss, schist	36% of basin harvested	3.1%	n/s	Annual sediment yield measured at a settling pond	n/a	No significant change in relation between SY and seasonal runoff		Troendle and Olsen (1993); Troendle and King (1987)	
Main Deadhorse Creek	Fraser Experimental Forest, Colorado	2.70	Glacial till gneiss, schist	10% of basin harvested	3.4%	n/s	Annual sediment yield measured at a settling pond	n/a	No significant change in relation between SY and seasonal runoff		Troendle and Olsen (1993); Troendle and King (1987)	
Baptiste Creek, B3	Stuart-Takla Fish-Forestry Interaction Project, Central Interior of B.C.	0.43	Ultra-basic intrusives mantled by glacial till	Clear-cut 55% of catchment area	0%	10-30 m buffer; all trees > 30 cm dbh harvested within 20 m from stream	Suspended sediment concentration	n/a	No significant change		Macdonald *et al.* (2003)	
Baptiste Creek, B5	Stuart-Takla Fish-Forestry Interaction Project Central Interior of B.C.	1.50	Ultra-basic intrusives mantled by glacial till	Clear-cut 53% of catchment area	~1.4 km/km^2	10-30 m buffer; all trees > 15-20 cm dbh harvested within 20 m from stream	Suspended sediment concentration	n/a	Increase in SSC > 100%, esp. following cuvert removal	Recovery to pre-harvest levels within 2-3 years	Macdonald *et al.* (2003)	
H.J. Andrews Watershed 1	Oregon Cascades	0.96	Altered volcaniclastics	100% clear-cut and broadcast burned; cable yarded	No roads	No buffer	Suspended sediment yield, computed from empirical relations with discharge	170	Suspended sediment yield higher after treatment	Suspended sediment yield appears to to have decreased, but not to pre-harvest levels	Grant and Wolff (1991)	Experiment confounded by landslides

TABLE 3. Summary of the Effect of Timber Harvesting and Riparian Management on Suspended Sediment Concentrations or Yields (post logging period) (cont'd.).

Catchment	Study Location	Area (km^2)	Geology	Harvesting Treatment	Roads	Riparian Treatment	Response Variable	Post-Logging SS Yield ($t/km^2/yr$)	Treatment Effect	Recovery	Reference	Comments
H.J. Andrews Watershed 3	Oregon Cascades	1.01	Altered volcaniclastics	25% patch cut and broadcast burned; cable yarded	2.6 km/km^2; 6% of catchment area	No buffer	Suspended sediment yield, computed from empirical relations with discharge	700	Suspended sediment yield higher after treatment	No basis to judge	Grand and Wolf (1991)	Experiment confounded by landslides and only one year of pre-impact data
Deer Creek	Oregon Coast Range	3.04	Sandstone	25% patch cut and 8% broadcast burned	4%	30 m riparian buffer along patch cut	Suspended sediment yield, computed from empirical relations with discharge	136	Significant increase up to 400%, for two post-treatment years	Recovery to pre-harvest levels within one or two years of mass movements	Brown and Krygier (1969); Beschta (1973)	Mass movement from roads elevated sediment yield seventh year after logging
Needle Branch	Oregon Coast Range	0.71	Sandstone	82% clear-cut and broadcast burned, 10% tractor yarded	5%	No buffer	Suspended sediment yield, computed from empirical relations with discharge	146	Significant increase up, to 1,000% for five post-treatment years	Recovery to pre-harvest levels in about six years	Brown and Krygier (1969); Beschta (1978)	
Subbasin ARF, North Fork Caspar Creek	Northern Coastal California	3.84	Sandstone and shale	46% clear-cut, 24% broadcast burned, 7% tractor yarded	1.8%	n/s	Storm-based-sediment yield	50.5	15% decrease in suspended sediment load		Lewis *et al.* (2001)	Main stem
Subbasin BAN, North Fork Caspar Creek	Northern Coastal California	0.10	Sandstone and shale	95% clear-cut, 13% tractor yarded	2.6%	n/s	Storm-based sediment yields	8.5	203% increase in load	No evidence of recovery over four-year post-harvest period	Lewis *et al.* (2001)	
Subbasin CAR, North Fork Caspar Creek	Northern Coastal California	0.26	Sandstone and shale	96% clear-cut, 9% tractor yarded	3%	n/s	Storm-based sediment yields	24.0	123% increase in load	No evidence of recovery over four-year post-harvest period	Lewis *et al.* (2001)	

TABLE 3. Summary of the Effect of Timber Harvesting and Riparian Management on Suspended Sediment Concentrations or Yields (post logging period) (cont'd.).

Catchment	Study Location	Area (km^2)	Geology	Harvesting Treatment	Roads	Riparian Treatment	Response Variable	Post-Logging SS Yield ($t/km^2/yr$)	Treatment Effect	Recovery	Reference	Comments
Subbasin DOL, North Fork Caspar Creek	Northern Coastal California	0.77	Sandstone and shale	36% clear-cut 6% tractor yarded, 34% broadcast burned	2.5%	n/s	Storm-based sediment yields	113.0	269% increase in load	No evidence of recovery over four-year post-harvest period	Lewis *et al.* (2001)	
Subbasin EAG, North Fork Caspar Creek	Northern Coastal California	0.27	Sandstone and shale	100% clear-cut and 98% broadcast birmed; 15% tractor yarded	4.9%	n/s	Storm-based sediment yields	71.0	238% increase in load	No evidence of recovery over four-year post-harvest period	Lewis *et al.* (2001)	
Subbasin FLY, North Fork Caspar Creek	Northern Coastal California	2.17	Sandstone and shale	45% clear-cut, 30% broadcast burned; 8% tractor yarded	1.8%	n/s	Storm-based sediment yields	53.6	3% decrease in load		Lewis *et al.* (2001)	Main stem
Subbasin GIB, North Fork Caspar Creek	Northern Coastal California	0.20	Sandstone and shale	100% clear-cut, 98% broadcast burned; 39% tractor yarded	4.2%	n/s	Storm-based sediment yields	35.8	200% increase in load	No evidence of recovery over four-year post-harvest period	Lewis *et al.* (2001)	
Subbasin JOH, North Fork Caspar Creek	Northern Coastal California	0.55	Sandstone and shale	30% clear-cut, 0% broadcast burned; 1% tractor yarded	2.0%	n/s	Storm-based sediment yields	66.7	23% decrease in load		Lewis *et al.* (2001)	Main stem
Subbasin KJE, North Fork Caspar Creek	Northern Coastal California	0.15	Sandstone and shale	97% clear-cut, 0% broadcast burned; 4% tractor yarded	7%	n/s	Storm-based sediment yields	82.1	40% decrease in load		Lewis *et al.* (2001)	

TABLE 3. Summary of the Effect of Timber Harvesting and Riparian Management on Suspended Sediment Concentrations or Yields (post logging period) (cont'd.).

Catchment	Study Location	Area (km^2)	Geology	Harvesting Treatment	Roads	Riparian Treatment	Response Variable	Post-Logging SS Yield (t/km^2/yr)	Treatment Effect	Recovery	Reference	Comments
Subbasin LAN, North Fork Caspar Creek	Northern Coastal California	1.56	Sandstone and shale	32% clear-cut, 20% broadcast burned; 2% tractor yarded	1%	n/s	Storm-based sediment yields	42.0	5% increase in load	No evidence of recovery over four-year post-harvest period	Lewis *et al.* (2001)	
Subbasin NFC, North Fork Caspar Creek	Northern Coastal California	4.73	Sandstone and shale	13% clear-cut, 20% broadcast burned; 8% tractor yarded	2%	n/s	Storm-based sediment yields	46.5	89% increase in load	No evidence of recovery over four-year post-harvest period	Lewis *et al.* (2001)	

n/s = Not specified.
n/a = Not available.

following harvesting reduces the internal cohesion of the soil mass, typically 3 to 15 years after logging (Ziemer, 1981; Sidle *et al.,* 1985), leading to increased probabilities of landslides.

Soil disturbance and sediment delivery to streams are commonly associated with construction of roads and landings, slash burning, and log skidding (Reid and Dunne, 1984; Christie and Fletcher, 1999; Jordan, 2001; Kreutzwiser *et al.,* 2001). The hydrologic and geomorphic effects of forest roads in particular have been the focus of many studies, given their demonstrated potential for negative impacts (Luce and Wemple, 2001). The use of tracked machinery such as hoe-forwarders may also cause soil disturbance, particularly if operated during periods of high soil moisture. Off-road vehicle use (motorcycle and snowmobile) can also generate significant surface erosion (Heede and King, 1990).

Road cut slopes and road fill can yield significant amounts of fine sediment by dry ravel, rain splash, frost, and mass erosion, particularly in the first year after road construction, as was demonstrated in Idaho (Megahan *et al.,* 2001). Most road generated sediment can originate from a relatively small fraction of the road network if there are major variations in the erosion potential of the road surfaces and cut slope (Wemple *et al.,* 1996; Henderson and Toews, 2001; Megahan *et al.,* 2001). Erosion from road surfaces appears to vary greatly depending on site specific factors such as the nature of fill materials, slope, drainage, age, usage, and maintenance. For example, Reid and Dunne (1984) found that heavily used roads generated 130 times more sediment (2,000 t/ha/year) than abandoned roads. Jordan (2001) found that the first storm that occurred following grading of road surfaces generated a significant increase in stream turbidity. On the other hand, Luce and Black (1999) found that sediment production from graded road plots was not significantly greater than from ungraded plots but that plots subjected to ditch cleaning had seven to eight times greater sediment production than graded or ungraded plots. Post-logging road treatment and removal can reduce the longer-term probability of sediment supply from road surface erosion and landside activity (Madej, 2001), although it can increase sediment delivery for one or more years following treatment (Macdonald *et al.,* 2003; Switalski *et al.,* 2004).

The significance of sediment sources for stream water quality will depend on whether they are connected to the stream by a channel, gully, or overland flow. If sources are not connected, sediment could be deposited on the soil surface before reaching a stream channel. Wemple *et al.* (1996) found that 57 percent of the road network was hydrologically connected to the stream network in the Western Cascades, Oregon.

Bilby *et al.* (1989) found that only 34 percent of road drainage points surveyed in Washington and Oregon appeared to flow directly into a stream channel. Similarly, Henderson and Toews (2001) estimated that only 36 percent of the sediment eroded from road surfaces could be delivered to the channel network in watersheds in southeastern British Columbia. Forest harvesting reduces transpiration and interception losses, resulting in higher soil moisture and water table levels (e.g., Adams *et al.,* 1991; Dhakal and Sidle, 2004). This change could increase the spatial and temporal frequency of saturation excess overland flow, potentially convert intermittent to perennial streams, and generally increase the connectivity of surface flow during storm events, all of which can increase sediment delivery to streams (Montgomery, 1994; Sidle *et al.,* 2000). For example, working in Pennsylvania, Lynch and Corbett (1990) observed an increase in sediment delivery to downstream reaches following conversion of an intermittent stream reach to perennial flow following harvest, in combination with increased sediment production through blowdown. Although such a process does not appear to have been reported in the Pacific Northwest, it could occur in areas with rolling topography, such as the extensive plateaus of the interior of British Columbia. Harvesting can also increase sediment generation by creating favorable microclimatic conditions for needle ice formation in exposed mineral soils such as along channel banks (Stott *et al.,* 2001) and on road cut slopes (Brown, 1985).

Sediment Generation and Transport in Riparian Buffers

Vegetated riparian zones function as sediment filters in agricultural and rangeland contexts (Cooper *et al.,* 1987; Phillips, 1989; Pearce *et al.,* 1998) and can also function as filters for sediment produced from areas of disturbed soil in forested catchments. Downslope travel distance depends on flow magnitude, density of ground obstructions, soil type, road width, whether road fill slopes are windrowed, and vegetation cover (Packer, 1967; Burroughs and King, 1989; Megahan and Ketcheson, 1996). Although predictive equations have been developed for downslope travel distance for road fill erosion (e.g., Megahan and Ketcheson, 1996), they are likely to be applicable only locally or regionally due to variations in climatic and hydrogeomorphic contexts.

Infiltration excess overland flow in severely disturbed soil and saturation excess overland flow may transport significant amounts of sediment from hillslopes to a stream even with an intact riparian buffer in place, as has been demonstrated in the Pacific Northwest and elsewhere (Belt and O'Loughlin, 1994; Rivenbark and Jackson, 2004; Gomi *et al.,* 2005). Because overland flow accumulations and paths depend on hillslope morphology and stream order, Bren (1998) suggested that riparian buffer zone dimensions should vary with respect to the hillslope contributing area adjacent to the channel reaches. In addition to width, the extent (length along channels) of riparian buffer zones may be an important control on sediment inputs to headwater streams in situations where channel extension into zero-order basins and concave hillslopes during wet conditions increases fine sediment availability.

Uprooting of streamside trees in riparian buffers can increase direct sediment delivery from root wads because wind throw rates are typically increased several times over pre-harvest levels (Ruel *et al.,* 2001; Stott *et al.,* 2001). Uprooted trees that fall into a channel can mobilize sediment by redirecting the flow into the bank or by forcing it to form a new channel, encouraging erosion. Lynch and Corbett (1990) attributed a post-harvest increase in turbidity to this process in a small stream in Pennsylvania. Grizzel and Wolff (1998) estimated that sediment delivery after one to three years of harvesting due to tree throw in riparian buffers in Washington averaged 0.67 m^3/100 m for nonfish bearing streams. This value can be compared to the pre-harvest delivery of approximately 1 m^3/100 m for Needle Branch in the Oregon Coast Range, estimated from the observed yield of 41 x 10^3 kg/yr (Harris, 1977), reach length of 2,200 m, and an assumed sediment density of 1,800 kg/m^3. It thus appears that sediment generation by riparian tree throw can be significant in relation to pre-logging sediment yields, especially in situations with deep, unconsolidated sediment in the riparian zone (Grizzel and Wolff, 1998).

Post-Harvest Changes in Suspended Sediment Regimes

A small number of studies have examined sediment response to forest harvest operations based on paired catchment experiments (Table 3). Most have focused on coastal (rain dominated and rain-on-snow dominated) catchments.

Suspended sediment yields doubled in the year after road building in the Deer Creek catchment in the Alsea Watershed Study, Oregon Coast Range, largely due to a road related landslide (Brown and Krygier, 1971). Sediment yields dropped to pretreatment levels within two years of harvesting but were elevated again six years after harvest as a result of several road related landslides. At Needle Branch, which was almost completely clear-cut and burned, sediment yields were roughly ten times greater than predicted from the control in the first post-treatment year, then recovered to pre-logging conditions within about six years after harvesting (Harris, 1977). Analysis of monthly yields showed that significant increases at Needle Branch occurred only in the early months of autumn and winter, prior to the seasonal peak discharge (Beschta, 1978). The lack of effect later in the winter and spring presumably reflects the exhaustion of sediment supply. The increased sediment yields at Needle Branch were attributed in large part to the severity of the broadcast burn, which exposed mineral soil to the streambank (Brown and Krygier, 1971) as well as potentially to the effects of streamside logging (Beschta, 1978).

Suspended sediment yields were higher after harvesting in two catchments in H.J. Andrews Experimental Forest in the Oregon Cascades (Grant and Wolff, 1991). In Watershed 1, which was cut and burned to the streambank, elevated yields were derived from several sources, including released debris stored in the channel (e.g., behind large woody debris), surface erosion, and debris slides following burning, and an active earthflow component within the drainage. Visual comparison of the time series for Watershed 1 and the control suggests that some level of recovery in yield occurred over the 22-year post-harvest period, though not to pre-harvest conditions. In Watershed 3, landslides in 1964 that originated from several sites on logging roads and from within the forest produced sediment yields more than an order of magnitude greater than in other years. Sediment yields in Watershed 3 recovered more quickly than in Watershed 1 – a debris flow went all the way to the Watershed 3 gauging station, clearing most sediment from the channel, whereas sediment due to debris flows in Watershed 1 remained in the channel and provided a continuing source of fine sediment.

Lewis *et al.* (2001) analyzed storm-based sediment yield data for eight independent subbasins of North Fork Caspar Creek in northern California, as well as at the basin outlet and at two other locations along the main stem. Prior to harvest, unit area sediment yields tended to increase with increasing catchment area. Stations along the main stem did not indicate increases in sediment yields after harvesting, while annual sediment yields from the tributary catchments increased from 123 to 269 percent, with little evidence of recovery through the four-year post-harvest study period. Lewis *et al.* (2001) attributed much of the increase in sediment yields to increased storm flow volumes. Fitting of two multiple regression models using different control basins suggested that sediment export increased with increasing length of unbuffered stream channel within clear-cuts and that post-harvest sediment export increased with increasing watershed area occupied by road cuts and fills. For the first model, separation of unbuffered stream length into components within burned and unburned clear-cuts significantly improved model fit, suggesting that burned clear-cut areas contributed more sediment than unburned clear-cuts. However, the high degree of correlation (r = 0.8) between length of unbuffered stream and area occupied by roads confounded the analysis. Field observations indicated that channel reaches subjected to intense broadcast burns experienced greater loss of woody debris and thus in-channel storage capacity, supporting the validity of length of unbuffered stream as a predictor variable, whereas field observations did not support the validity of roaded area as a predictor variable for sediment yield.

Macdonald *et al.* (2003) monitored suspended sediment concentrations during spring freshets in the central interior of British Columbia. Two treatment catchments were approximately 55 percent clear-cut harvested with partial retention buffers along the entire stream length in the cut block (Table 3). For one watershed that was harvested without roads, there was no significant increase in SSC following harvest, even though blow down in the partial retention buffer reduced canopy density from about 36 percent to 10 percent. The other stream had two road crossings and exhibited significant increases in SSC for three years after harvest, with recovery to pre-harvest levels in the fourth year. The highest sediment yields occurred in the second post-harvest year, following removal of the culvert at the upper road crossing during road deactivation.

Three studies reported annual yields in snowmelt-dominated catchments based on accumulation in detention ponds. Ketcheson *et al.* (1999) found that road construction in two catchments in the Idaho Batholith (drainage areas < 130 ha) increased annual sediment yields (measured at a retention pond), but the effect was statistically significant only for the first year after construction. Troendle and Olsen (1993) reported that sediment yields for North Fork Deadhorse Creek were significantly higher after harvest, based on an analysis of covariance with suspended sediment yields from a control stream (Table 3). However, the lack of a statistically significant change in the relation between sediment yield and seasonal flow suggests that the post-harvest increase in yield was the result of a post-harvest increase in discharge, which increased the ability of the stream to entrain and transport sediment from internal sources rather than being the result of increased supply. Sediment yields from Fool Creek (harvested) averaged almost three times greater than those for Deadhorse Creek (unharvested) and four times greater than those for Lexen Creek (unharvested) in the Fraser Experimental Forest (Leaf, 1970). The lack of predisturbance data, plus the confounding effect of flow variations among the years, prohibits the statistical evaluation of the treatment effect. However, Grant and Hayes (2000) found that increases in peak flow had moderate influences in sediment yield after harvesting. They concluded that increases in sediment supplies significantly increased suspended sediment yields based on 40 years of monitoring Watersheds 1 and 2 in the H.J. Andrews Experimental Forest.

An important question is whether harvesting within riparian buffers influences suspended sediment dynamics. No published studies in the Pacific Northwest appear to have examined this issue using a replicated study design. Working on headwater streams in Mississippi, Keim and Schoenholtz (1999) monitored post-harvest suspended load and turbidity in headwater streams that were subject to four types of riparian management treatments (unrestricted harvest, cable only, no harvest, reference). Total suspended sediment yield increased in streams with unrestricted harvesting, whereas no significant increases were found in streams where there was no soil disturbance adjacent to the channel. However, streamside management zones did not effectively trap sediment generated outside the riparian zones. Similarly, Plamondon (1982) demonstrated that sediment concentrations were not significantly different between undisturbed and disturbed catchments in Quebec at sites where the streams were protected by riparian buffer zones or the soil was untouched by skidders. However, these studies were conducted at sites with lower hillslope and channel gradients than would be found in the steep-land regions of the Pacific Northwest and may be most relevant to the interior plateau regions of British Columbia.

Changes of In-Channel Fine Sediment Due to Logging

Relatively few studies have examined post-harvest infiltration of fine sediment into the bed of small streams. Bilby (1985) found that most of the sediment produced from a logging road was less than 0.004 mm in diameter. Although deposition of this sediment within the channel did occur at low flows, it was scoured from the channel and transported downstream during higher flows. Working in the Turkey Lakes Watershed in Ontario, Canada, Kreutzweiser and Capell (2001) found significant increases in fine sediment within the bed at a site affected by a logging road but no harvesting, while road construction resulted in similar increases in a selection cut with no riparian buffer (40 percent canopy removal), and no detectable increases occurred in a shelterwood cut (50 percent canopy removal) with no logging roads immediately upstream. In a study in Tasmania, Davies and Nelson (1993) found that fine sediment infiltration was enhanced two to three times by logging around ephemeral streams.

DISCUSSION AND CONCLUSIONS

Relative Effects of Changes in Hydrology and Sediment Supply

In many cases, the main cause of increased suspended sediment yield could be clearly linked to an increase in sediment availability, particularly where roads were the main source, as was the case at Flynn Creek in Oregon (Beschta, 1978) and Stream B5 in interior British Columbia (Macdonald *et al.*, 2003). Landslides have also been clearly implicated as important sediment sources (e.g., at Watersheds 1 and 3 in the H.J. Andrews Experimental Forest) (Grant and Wolff, 1991). In other cases, changes in streamflow appeared to be more important. For example, Troendle and Olsen (1993) argued that sediment supply from external sources did not change after logging at North Fork Deadhorse Creek, based on the lack of change in the relation between sediment yield and discharge. Lewis *et al.* (2001) similarly argued that much of the increase in sediment yield at North Fork Caspar Creek was caused by increased streamflow, which caused increased recruitment from within-channel sources. An extension of this hypothesis is that increased flows after harvesting may be correlated with higher water tables and hence greater surface-flow connectivity between the perennial channel network and hillslopes via zero-order basins and intermittent reaches (Dhakal and Sidle, 2004). That is, it is not solely the increased flow in the perennial channel that increases sediment transport, but also the accompanying increase in catchment scale hydrologic connectivity and the more frequent delivery of sediment from hillslopes, zero-order basins, and intermittent channels, especially where these surfaces have been subject to soil disturbance due to harvest operations (Sidle *et al.*, 2000; Gomi *et al.*, 2002). This mechanism is likely to be most relevant in areas of rolling topography such as the interior plateaus of British Columbia, though it may occur in situations where soil disturbance occurs adjacent to zero-order basins or ephemeral channels.

Recovery Rates

Rates of recovery to pre-logging conditions were variable and appeared to depend on the nature of the disturbance, in particular whether increased sediment yields were associated with the primary disturbance from logging activity or secondary disturbance such as mass movement (Figure 2). At Deer Creek in the Oregon Coast Range and Stream B5 in the central interior of British Columbia, where roads were the dominant sediment source, recovery appeared to occur within two to three years after the roads became dormant. This result is in accordance with studies such as that by Reid and Dunne (1984) that indicate that sediment generation from roads decreases by one or two orders of magnitude when they are no longer traveled or actively maintained, except where delayed road related slides occurred (Figure 2). At Needle Branch, which experienced catchment-wide soil disturbance associated with clear-cut logging followed by prescribed fire, recovery took about six years, presumably related to the regrowth of vegetation in the cut block. At H.J. Andrews Watersheds 1 and 3, where mass movements fundamentally modified channel morphology and sediment deposits, sediment yields appeared to remain elevated for over 20 years (Grant and Wolff, 1991) (Figure 2). Episodic mass movements associated with failure of road fills or resulting from root decay may occur decades after harvesting, causing new periods of elevated suspended sediment.

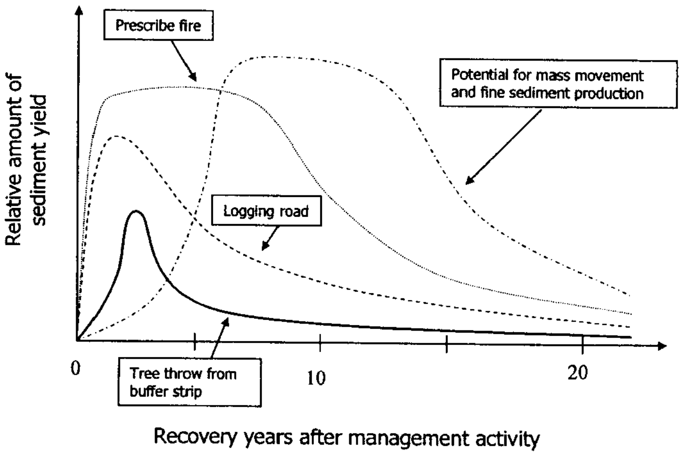

Figure 2. Relative Durations and Recovery Rates for Increased Suspended Sediment Yield Associated With Forest Harvesting and Other Disturbances.

Efficacy of Riparian Buffers in Protecting Against Sediment Impacts

Riparian buffers can potentially protect streams from sediment input by acting as filters for overland flow traversing the riparian zone from the hillslope to the stream. In addition, the buffer ensures that physical disturbance (e.g., due to tractor yarding), is minimized in the zone directly adjacent to the stream. In most of the experimental watershed studies, streams with buffers ranging from about 10 to 30 m wide had relatively small increases in sediment yield, except where sediment was generated by mass movements or road erosion (e.g., Deer Creek, Stream B5). However, roads and skid trails that cross zero-order basins can create hydrological connections and sediment transport to channels even with 20 to 30 m wide buffers (Wemple *et al.,* 1996; Gomi *et al.,* 2005). Bren and Turner (1980) argued that extending riparian reserves toward zero-order basins would help maintain natural hydrogeomorphic processes in these upslope areas. The protective role of riparian buffers is supported by the statistical modeling at North Fork Caspar Creek, where length of unbuffered stream channel was a statistically significant predictor variable for the amount of suspended sediment yield.

The results from Keim and Schoenholtz (1999), the Turkey Lakes study (Kreutzwiser and Capell, 2001), and Stream B3 (Macdonald *et al.,* 2003) suggest that harvesting can occur in a riparian zone without causing increases in suspended sediment, at least for moderate levels of harvest and where soil disturbance in the riparian zone is minimized. However, it is unclear whether these results can be safely extended to other landscapes, such as rain dominated steeplands.

Although blow down of streamside trees in buffers has the potential to release significant amounts of sediment by uprooting (Grizzel and Wolff, 1998), this did not appear to have a significant effect for Stream B3 in the central interior of British Columbia (Macdonald *et al.,* 2003). In that case, SSC did not increase after harvest, despite a significant amount of blow down within the riparian buffer. However, it was apparently an important effect for a small stream in Pennsylvania (Lynch and Corbett, 1990).

Scale Effects

Only two studies appear to have estimated harvesting related changes in sediment yield at multiple scales (Troendle and Olsen, 1993; Lewis *et al.,* 2001), and these examined a relatively small range of catchment sizes (from 10 to 470 ha). In both cases, headwater tributaries were more sensitive than downstream reaches, and the authors inferred that sediment yield increases were caused by the post-harvest increases in flow rather than an increase in sediment supply. In support of these findings for a much larger catchment, Sullivan (1985) found that there were no detectable changes in sediment yield related to forest harvesting (40 percent of study area was logged) in a 285 km^2 catchment.

Methodological Considerations

Because suspended sediment concentrations can vary dramatically within and between storms, with marked hysteresis in relations between SSC and discharge on both of those time scales, temporally high-resolution measurements of SSC are required (Beschta, 1978; Thomas, 1988; Church, 1998; Nistor and Church, 2005). Perhaps the best strategy for accurate estimation of suspended sediment concentrations is to combine continuous measurements of turbidity using optical back scatter probes with programmable samplers, which can be controlled to begin sampling when turbidity rises above some threshold background level.

The temporal resolution of the suspended sediment data is a fundamental consideration when attempting to assess the potential for ecological impacts. Several studies have examined changes in monthly, seasonal, or annual yields after forest harvesting. However, it is difficult to assess the ecological significance of these yield data; short-term suspended sediment concentrations may be more critical. As mentioned above, generating such records can be challenging, given current technology, particularly for remote sites.

Experimental designs involving both pre-treatment and post-treatment data, and untreated controls, are required to detect effects of forest harvesting (Swank *et al.*, 2001). Lewis *et al.* (2001) conducted what appears to be the most comprehensive experiment, involving multiple treatment catchments and multiple controls. They also employed sophisticated sampling protocols to increase the accuracy of their yield estimates, as well as sophisticated statistical modeling to account for spatial correlation among catchments. However, even in that situation, it was difficult to draw inferences about the causal factors controlling changes in sediment yield from the statistical results.

A fundamental problem in generalizing experimental results is that catchments are typically subjected to treatments having multiple dimensions (e.g., percent of catchment harvested, riparian treatment, characteristics of road network), which may be difficult to replicate given the peculiarities of individual catchments. Lewis *et al.* (2001) found that a correlation between levels of two factors (length of unbuffered stream and area of roads) confounded the statistical estimation of those effects. Furthermore, unplanned effects in the form of road-related landslides (e.g., at Deer Creek and HJA Watershed 3) can confound the effects of canopy removal and surface erosion from roads. Because landslides can occur decades after harvest (e.g., 11 and 21 years after logging in WS10 and 5 and 37 years in WS 3 in H.J. Andrews Experimental Forest), long term post-treatment monitoring is required to develop a comprehensive understanding of logging impacts and recovery processes.

Variability in suspended sediment concentration of control streams may occur due to natural landslides, slope failure, soil creep, and forest fires. In addition, changes in discharge due to climate variations (e.g., dry and wet years due to ENSO and/or Pacific Decadal Oscillation) potentially confound suspended sediment supply and transport and may change the status of perennial and ephemeral channels. Therefore, replication of both control and treatment streams in paired catchment approaches would be valuable for minimizing the potential confounding of the natural spatial and temporal variability of suspended sediment transport with the impacts of timber harvesting.

Research Needs

In most of the experimental studies, much of the observed response and the rate of recovery could be qualitatively related to the nature of the treatments, particularly where roads or road related landslides were dominant sediment sources. However, an issue that cannot be definitively answered based on existing studies relates to the relative roles of hydrologic changes versus changes in sediment supply from external sources after harvesting. Hydrology-related changes in sediment yield could result from increased transport capacity in the perennial channel network or increased surface flow connectivity associated with higher moisture conditions following harvest, which could allow greater recruitment of sediment during storm events from hillslopes, zero-order basins, and normally intermittent channel segments. Addressing this issue would require an integrated approach in which field based process studies (e.g., identifying sediment source areas and changes in sediment storage in the channel and bed) are conducted within the context of paired catchment experiments. Ideally, such studies would also incorporate an integrated modeling component to assist in linking plot scale process observations to catchment scale sediment response.

The fate of sediment that has infiltrated bed sediment is poorly understood. In larger gravel bed streams, fines appear to be flushed from the gravels every year, at least from the active layer. In headwater streams, where significant bed-load transport may be relatively infrequent (Benda *et al.*, 2005), it is unclear whether fines get flushed during high flows or whether they accumulate to the point that they clog the available pore space with attendant consequences for hyporheic flow, oxygen supply, and benthic organisms. Another knowledge gap relates to the routing of fine sediment through headwater streams to downstream reaches and the potential for downstream cumulative effects associated with harvesting in headwater catchments.

Many of the paired catchment studies in the Pacific Northwest were conducted in the 1970s and 1980s and applied treatments that are no longer used (e.g., clear-cutting with hot broadcast burning), and the results may not be applicable to newer practices such as clear-cutting with partial retention buffers and current standards for road design and construction. Another barrier to transferring research results is the effect of varying hydrogeomorphology, which influences both the nature of sediment sources and hydrologic response. Further research is needed to relate potential impacts on sediment generation and delivery to site specific attributes. For example, Bren (1998) advocated the use of topographic indices in buffer design, but there is tremendous scope for further work employing both static predictors and dynamic modeling of hydrologic and geomorphic processes (e.g., Benda and Dunne, 1997; Lancaster *et al.*, 2003). An important consideration for both field studies and modeling is the legacy of past practices, which may have a strong influence on the hydrogeomorphic response to future forestry activities.

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