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Key Points:

- Forestry can occur with limited inputs of fine sediment to streams
- Change thresholds provide a biological context to test results
- Turbidity and flow are not consistent predictors of suspended sediment

Supporting Information:

- Supporting Information S1

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Suspended sediment and turbidity after road construction/improvement and forest harvest in streams of the Trask River Watershed Study, Oregon

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Abstract Transport of fine-grained sediment from unpaved forest roads into streams is a concern due to the potential negative effects of additional suspended sediment on aquatic ecosystems. Here we compared turbidity and suspended sediment concentration (SSC) dynamics in five nonfish bearing coastal Oregon streams above and below road crossings, during three consecutive time periods ("before", "after road construction/improvement", and "after forest harvest and hauling"). We hypothesized that the combined effects of road construction/improvement and the hauling following forest harvest would increase turbidity and SSC in these streams. We tested whether the differences between paired samples from above and below road crossing exceeded various biological thresholds, using literature values of biological responses to increases in SSC and turbidity. Overall, we found minimal increases of both turbidity and SSC after road improvement, forest harvest, and hauling. Because flow is often used as a surrogate for turbidity or SSC we examined these relationships using data from locations above road crossings that were unaffected by roads or forest harvest and hauling. In addition, we examined the association between turbidity and SSC for these background locations. We found a positive, but in some cases weak association between flow and turbidity, and between flow and SSC; the relationship between turbidity and SSC was more robust, but also inconsistent among sites over time. In these low order streams, the concentrations and transport of suspended sediment seems to be highly influenced by the variability of local conditions. Our study provides an expanded understanding of current forest road management practice effects on fine-grained sediment in streams and introduces alternative metrics using multiple thresholds to evaluate potential indicators of biological relevance.

1. Introduction

The increase of fine-grained suspended sediment (<2 mm) in freshwaters has been identified as an important contributor to both declines in populations of aquatic organisms and negative effects at the ecosystem level (see literature review in supporting information Table S1; (supporting information sources can be found in Appendix A); *Newcombe and Macdonald* [1991], *Wood and Armitage* [1997], and *Henley et al.* [2000]). Even relatively small changes in suspended sediment concentrations (SSC) can adversely affect aquatic biodiversity, especially affecting species with a narrow range of suspended sediment tolerance [*Olson and Hawkins*, 2017]. For this reason, regulatory agencies have been using criteria to regulate sediments in inland water bodies often using turbidity as a surrogate for suspended sediments [*US Environmental Protection Agency* (*EPA*), 2006].

Unpaved roads on forest lands can have adverse effects on stream biota [*Cederholm et al.*, 1981; *Wood and Armitage*, 1997] because of increased SSC originating from the erosion of road surfaces [*Brown and Krygier*, 1971; *Reid and Dunne*, 1984; *Bilby et al.*, 1989; *Lane and Sheridan*, 2002; *Gomi et al.*, 2005]. Many studies have shown evidence of an overall increase in fine sediment delivery to streams after road construction [*Brown and Krygier*, 1971; *Beschta*, 1978; *Bilby et al.*, 1989; *Megahan et al.*, 2001; *Sidle et al.*, 2004]. Often, this increase is higher when road construction is coupled with forest harvest [*Fredriksen*, 1973; *Brown and Krygier*, 1971; *Betchta*, 1978] and hauling [*Wooldridge*, 1979; *Reid and Dunne*, 1984; *Bilby et al.*, 1989; *Ziegler et al.*, 2001].

Further, the magnitude of increased SSC in streams depends on site-specific conditions such as stream flow [*Walling*, 1977; *Reid and Dunne*, 1984; *Williams*, 1989], channel morphology [*Benda and Dunne*, 1997; *Hassan et al*., 2005], and the availability of sediment to be transported [*Grant and Wolff*, 1991; *Benda and Dunne*, 1997].

However, forest road construction and maintenance, forest harvest and hauling practices have changed substantially over the last several decades in order to reduce chronic and episodic sediment delivery. In the 1940s to 1960s, forest roads were built on unstable material on steep slopes; bulldozers excavated material that was pushed over onto steep slopes below, typically called "sidecast" [*National Council for Air and Stream Improvement, Inc*. (*NCASI*), 2009]. This construction method contained a large amount of buried organic material that eventually decomposed and led to numerous slumps and landslides. By the 1980s, most roads, especially on steep slopes, had excess material hauled away rather than sidecast [*NCASI*, 2009]. Early roads and their ditches also delivered water and sediment directly into streams [*Luce and Black*, 1999; *Wemple et al*., 1996]. Current forest management practices have been refined to mitigate and minimize the increased sediment from roads [e.g., *Anderson and Lockaby*, 2011; *Wear et al*., 2013; *van Meerveld et al*., 2014], but there is still concern about whether current practices are as effective as possible in reducing sediment transport from roads.

The design and construction of roads [*Keller and Sherar*, 2003; *Rodgers et al*., 2009] and their degree of hydrological connectivity to the stream network [*Wemple et al*., 1996; *Luce and Black*, 1999; *Croke et al*., 2005] have also been revised over time. In western North America, a few studies have examined the magnitude of change in suspended sediment transport in streams associated with contemporary forest road management practices [e.g., *Sugden and Woods*, 2007; *Zégre*, 2008; *Meadows*, 2009]. For example, *Sugden and Woods* [2007] report that by a reduction in the frequency of grading sediment yields from forest roads in Montana decreased. In Oregon, *Zégre* [2008] and *Meadows* [2009] show the importance of using multiple temporal scales to evaluate the effects of contemporary forest harvest on sediment yields and turbidity, respectively. Yet, high natural variability in sediment transport in streams makes it difficult to identify the specific contribution of forest management practices to SSC.

Here we hypothesize that the combined effects of road construction/improvement-forest harvest and hauling increase both turbidity and SSC in adjacent streams. To test our hypothesis, we compare the magnitude of SSC and turbidity above and below road crossings at five nonfish bearing streams during three consecutive time periods, designated as "before", "after the road construction/improvement", and "after forest harvest and hauling". Specifically, we developed the study design to capture the maximum susceptibility of the stream network to changes in fine sediment delivery that usually occurs during the first wet season following road construction/improvement [*Brown and Krygier*, 1971; *Swanson and Dyrness*, 1975; *Megahan et al*., 2001; *Gomi et al*., 2005; *Bathurst and Iroumé*, 2014].

We address two main questions: (1) Do road crossings in forested areas lead to increased fine-suspended sediment downstream after road construction, improvements and after forest harvest and log hauling? (2) If so, how frequently does sediment transport downstream occur? In addition, because turbidity and flow are often used as a surrogate for suspended sediment concentrations [*Walling*, 1977; *Williams*, 1989; *Lewis* 1996; *Uhrich and Bragg*, 2003; *Zégre*, 2008], we use these data to examine the consistency of their relationships under conditions unaffected by road improvements and forest management. Collectively, this study has the potential to provide scientists, policy makers, and resource managers with an expanded understanding of the effects of contemporary forest road practices on concentrations of suspended fine sediment in streams.

2. Study Area and Historical Context

This study was part of the Trask River Watershed Study (TRWS), which is a multidisciplinary and long-term research project, designed to evaluate the effects of current forest practices on in-stream processes, water quality, and food webs. The TRWS utilizes a before-after, replicated, paired watershed approach to evaluate the effects of forest harvest on state, private and federal forestlands in nonfish bearing headwater basins (21–48 ha). The TRWS is located on the East Fork of the South Fork of the Trask River in the Northern Oregon Coast Range near Trask Mountain (Figure 1). The streams draining the study area flow into the mainstem Trask River, which flows into Tillamook Bay. The TRWS area is owned and managed by the Oregon Department of Forestry (ODF) and Weyerhaeuser Company with a small portion belonging to the Bureau of Land

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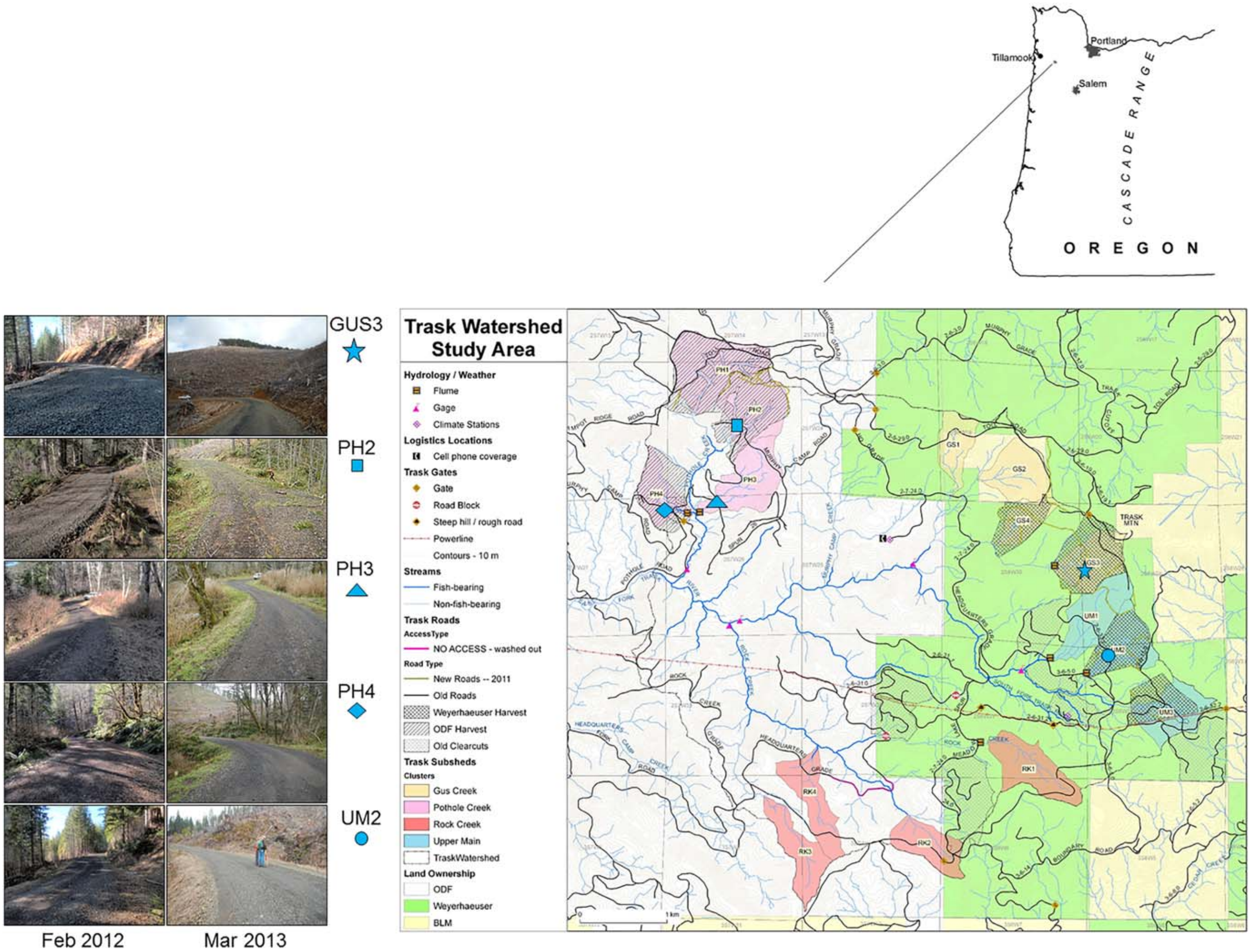

Figure 1. (right) Map of the Trask River Watershed Study (TRWS) and respective study sites. (left) Road crossing conditions during the winter (2012) after road improvements and during the winter (2013) after forest harvest and hauling. The reference site PH3 was not harvested; the road was not upgraded and received no hauling.

Management. Average annual precipitation is 2000 mm. December often has the highest rainfall, with an average of more than 300 mm during the month. Summers are relatively dry, with July rainfall less than 15 mm. Average air temperatures are generally mild throughout the year, though due to the relatively high elevation of the study area the upper portion can experience average minimum temperature less than 5°C. Snow accumulation above 760 m of elevation in the study area is common in January and February.

The geology of the TRWS area is composed of both volcanic and sedimentary formations [*Wells et al*., 1994]. The surficial geomorphic expression of the underlying geology includes large, ancient earthflows, long smooth slopes and some steeply dissected stream-adjacent slopes. Background sediment delivery processes in the area are mainly driven by large ancient deep-seated earthflows with some past debris flows from steep dissected volcanic terrain (Table 1) [*Benda and Dunne*, 1997]. For the most part, the TRWS area is made up of slopes that are relatively stable and neither steep nor convergent. The steepest channels (>20%) are generally located within the steep, highly dissected volcanic terrain where hillslopes average 60% or more [*Turner et al*., 2007]. The streams in the various geomorphic units mirror the terrain in which they are embedded. The flatter areas where there are alluvial terraces tend to have low gradient channels that are areas of sediment accumulation. The steepest channels (>20%) are mainly located within the steep, highly dissected volcanic terrain. The soil texture of the TRWS area is similar across the watershed with most of the area mapped as loam to gravely.

Table 1. Characteristics of the Study Sites, With Paired Samplers (a) Above and (b) Below the Road Segment[a]

	GUS3	PH2	PH3	PH4	UM2
Road crossing type	Treatment, new	Treatment, existing	Reference, existing	Treatment, existing	Treatment, existing
Hydrological connectivity (Ditch length; m)	71.0[b]	55.5	171.0	50.3	65.5[c]
Surfacing change	New road, rocked	Rock added	Unsurfaced to rock		Rock added
Road area connected (m^2)	465	121	158	307	158
Road gradient (%)	0–1%	4%	5%	2.5%	5%
Ditch condition	Nonvegetated	Minimal Vegetated	Vegetated	Vegetated	Nonvegetated
Culvert dimensions (diameter [m] × length [m])	0.76 × 18	0.76 × 9	0.61 × 18	0.61 × 15	0.76 × 12
Culvert gradient, condition	27%	14%	6%	6%	9%
Distance from road to sampler (a/b)	26/25	12/8	26/26	28/151	26/26
Stream gradient (%) above and below road (a/b)	20.8/69.7	39.8/24.4	15.9/15.0	6.4/20.6	61.8/24.3
Stream wetted width (m)	0.68	0.94	1.06	0.68	0.72
Watershed area above lower road crossing (ha)	12.75	10.60	36.08	16.98	5.59
Geological context	Intrusive/stony loam	Ancient landslide/loam to very gravelly loam	Ancient landslide/ loam to very gravelly loam	Above road: volcanic; below road ancient landslide/loam to very gravelly loam	Sedimentary/ silt loam
Harvest area (ha)	36.66	41.48	0	26.39	32.33
Leave area (ha)	1.17[d]	6.23	NA	2.12	1.29[d]
Watershed treated (%)	93.9	78.2[e]	0[e]	91.9[e]	82.6
Harvest and yarding type[f]	CC; cable	MC/RC	Not harvested	MC; ground some cable	CC; cable, ground
Stream leave tree requirements	No overstory	10 m no touch	NA	10 m no touch	No overstory
Large truck traffic	1330	<600	0	600	1980
Downstream flume within watershed (y/n)	Y	None, flow interpolated	Y	Y	Y

[a]Also descriptions of road condition, upstream harvest treatments and degree of hydrological connectivity of roads and streams (see also photographs of sites in supporting information Figure S1).
[b]Road/ditch flow to stream crossing is indeterminate-no ditch feature and flat grade.
[c]A portion of the road surface may sheet flow to outlet side of culvert.
[d]In private forests, location of leave trees is site specific. In GUS3, leave trees were on the ridges, and in UM2, they were in riparian area.
[e]Represents the harvest area minus leave area and the resulting value is divided by the watershed area. Thinning had occurred in the State forests in 2004.
[f]The watershed study treatments included clear-cut harvest (CC), retention harvest (RH), modified clear-cut and thinning (MC). For state and federal lands 7.62–15.24 m stream buffers were left on nonfish bearing streams while private forest lands in the Coast Range did not require overstory retention. CC = A clear-cut was a harvest where few seedlings, saplings or poles remain. MC = Clear-cuts were modified to leave residual green trees, snags, or trees destined to become snags specifically for their biological or environmental values. RC = Retention cuts were similar to partial cuts. Focus of future management will be on the new/young trees in the stand, rather than the residual trees.

Forests in the TRWS area have been influenced by several large-scale human-related disturbances. A series of forest fires, collectively called the Tillamook Burn, occurred between 1933 and 1951. Most merchantable remaining trees were salvage logged. As a result, the forests of the watershed are predominantly 50 year old Douglas-fir (*Pseudotsuga menziesii*) with some areas of hardwood, mainly red alder (*Alnus rubra*). The earliest transportation network (Figure 1) in the study area was a railroad grade (Headquarters Grade Road) and a stagecoach road (Toll Road). The road network expanded with harvest and subsequent salvage following the large fires. The current road network utilizes the extent of the old railroad grade as well as several roads that were previously established for harvest and salvage (Table 1). Several kilometers of abandoned skid roads are still evident throughout the watershed.

3. Material and Methods

3.1. Road Improvement/Construction and Forest Management

The harvest of the study watersheds in the TRWS necessitated the upgrade and construction of new roads. These small watersheds were harvested by thinning, retention or clear-cut (Table 1). We studied five road crossings within the TRWS area (Figure 1). Four road crossings received road upgrades or new roads and timber hauling (Table 1). We instrumented two sites on Oregon State Forests, Pothole 2 (PH2), and Pothole 4 (PH4) and two sites on privately owned forests, Upper Main 2 (UM2) and Gus3 (GUS3). The crossing at GUS3 consisted of a newly created 4 m high road fill over an 18 m culvert. The road crossing at UM2 was built prior to 1997 and reconstructed in 2007. Additional gravel was added in 2011 before the forest harvest occurred (2012). The original road crossing PH2, PH3, and PH4 was a rail road built in the 1920s and converted to logging roads in the 1930s to 1940s. This road system was used for thinning in 2001–2002. Our reference site, Pothole 3 (PH3) was not affected by road upgrades, forest harvest or used to convey haul. At the time of road building, no harvest was occurring in any of the watersheds above the study sites. GUS3 had one preexisting road at the top of the watershed, approximately 150 m above our study site.

Forest harvest occurred upstream of the road crossings in all basins except PH3 (reference site) in 2012. Harvests on State Forests require no-harvest riparian buffers that range between 8 and 17 m (horizontal distance width) on small fishless perennial streams. The actual width depends on site conditions, but as applied on these streams, buffers were approximately 10 m wide on each side of the stream. The seasonal portion of these streams did not meet the criteria for additional riparian buffering (e.g., high debris-flow potential). Streams through private forests (GUS3 and UM2) were not required to retain overstory in the riparian areas (Table 1).

The spur road accessing both GUS3 and UM2 received the most haul (1330 and 1980 log truck crossings, respectively). The reference site PH3 had the longest hydrologic connectivity (ditch line) at 52 m with other sites varying between 15 and 22 m. Watershed areas draining to the road crossing ranged from 26.4 to 45.1 ha. The site UM2 exhibited the steepest above-road stream gradient (61.8%) while GUS3 had the steepest below-road gradient (69.7%). Gradients were lowest for PH3 and PH4. The site with most area of road connected to the stream was GUS3 followed by PH4 whereas the longest ditch connected to the stream was at UM2 and the reference site PH3. Discharge was measured using precalibrated Montana fiberglass flumes at the downstream extent of harvested watershed in four of the five road crossing sites (i.e., GUS3, PH3, PH4, and UM2). The flumes were 100–200 m downstream of the road crossing. For PH2, discharge data were interpolated using area-weighted measurements from existing nearby flumes (Figure 1).

3.2. Study Design and Timeline

This study was conducted primarily during fall, winter, and early spring from 2010 to 2013. November 2010 to April 2011 represented a period prior to road construction or upgrading activities (hereafter "before"). Road work occurred during the summer of 2011 and early fall of 2011. September 2011 to May 2012 represented a postroadwork scenario after road improvement, (hereafter "RI"). Harvest began in spring 2012 and was completed at all sites by early fall 2012. October 2012 to March 2013 represented a postroad improvement plus postforest harvest and hauling data collection period (hereafter "RI + FHH"). No sampling or measurements occurred during summer harvest and hauling since tree-falling, yarding, and haul occurred simultaneously and precluded equipment and researchers from being within the harvest units. The harvest occurred during a low flow period where the transport of fine sediment would be expected to be minimal.

We obtained water samples from five streams above and below road crossings (Table 1) using automatic pump samplers (Teledyne Isco, Lincoln, NE). Samplers were placed outside of the stream bankfull width with hoses extending into the stream channel, above and below each road crossing. We used a variety of Isco models: 2910, 2700, 3700, and 6712. We did not verify the sampling efficiency of each Isco; therefore, sampler intake velocities may have differed. All samples were collected using 6.4 mm (inside) diameter tubing with a screened intake, using 4.0 mm mesh. This size of opening may have limited large sediment from being sampled, but we did not observe clogging of the screen following high-flow events. The tubing was attached to submerged rebar in a stream pool. We avoided drop-pools due to the possibility of drawing current-agitated sediment into samples. Individual pump samplers were referred to by their site abbreviation and location above (a) or below (b) a road crossing (e.g., PH2b refers to the Isco below the road at Pothole 2). Distances between the above and below road crossing locations ranged between 20 and 179 m. There were no other tributaries joining the stream between the above and below locations. Water samples were taken during the time periods "before", "RI", and "RI + FHH". At four of five sites, water samples were collected in individual containers every 12 h (noon and midnight). Samples at PH4 were collected only at midnight because the downstream sampler was installed for another study with a different sampling regime. Target volume per sample was 400 mL.

We only processed a subset of all bottles collected due to our processing capacity. Our highest priority were storm samples and we processed all samples from storm events. We used the telemetered stream gage data from UM1 to determine which subset of the collected samples were to be analyzed (Figure 1). We evaluated samples starting 12 h prior to a rising limb of UM1's hydrograph and ending 12 h after passing its falling limb, to accommodate for differences in the timing of the other watersheds' hydrograph responses and to quantify prestorm transport. For nonstorm periods, we randomly selected paired samples by stream crossing with a target of processing between 40 and 60 bottles (28–42% of bottles collected) per week. At PH4 we processed every bottle collected. More than 78% of the processed water samples were taken under flow conditions above the median flow and almost 40% of samples were taken during high-flow conditions (above 80th flow percentile of the respective time period). Our sampling approach was designed to quantify conditions when the majority of the transport of fine sediment occurred (see more details about the distribution of sampling efforts across sites, time periods and discharge in supporting information Figure S1). Sampling occurred during as comparable seasons as possible across time periods. Specifically, for the time period "before" 80% of water samples were collected between November and March. Similarly, for the "RI" and "RI + FHH" time periods, 93% and 95% of water samples, respectively, were collected between these months.

3.3. Turbidity and Suspended Solid Sediment Concentration

Turbidity (Nephelometric Turbidity Units, "NTU") was measured on all selected samples within 24 h of bottle collection, using the U.S. Environmental Protection Agency standard method [*EPA*, 1993]. Between November 2010 and June 2012, we used an Orbeco-Hellige portable turbidimeter Model 966 (Resolution: 0.01 NTU: Accuracy: ±3%). We switched to a Hach 2100p turbidimeter (Resolution: 0.01 NTU: Accuracy: ±2%) in October 2012. We performed 25 paired comparisons of water samples with turbidities in our most common range (0.00–7.36 NTU) and found no statistically significant difference in performance between the two instruments.

Water samples were processed for suspended solid sediment concentrations (SSC; mg L^{-1}) according to *Toman* [2007]. Bottles containing samples were weighed, samples were filtered, and then bottles were dried and reweighed to determine both bottle and sample mass. During filtration all bottles were rinsed with additional deionized water, which was then poured through the same filter. Filtering was accomplished using suction filtration on 55 mm Buchner funnels containing ashed, dried, and preweighed 1.5 μm glass fiber filters (Whatman 934-AH). Filters with sediment were then dried at 100°C for at least 24 h prior to weighing. Mass of filters was measured to the ten thousandth of a gram.

3.4. Data Analysis

Because it is not possible to plan equal climatic and hydrologic conditions during a multiyear study, our analysis was not intended to statistically compare fine sediment transport for specific storm events or contrast results among time periods or sites. Rather, we used the paired upstream/downstream samples at each road crossing to assess the change in suspended sediment and turbidity within the three different time periods.

Total precipitation for these three time periods was comparable (supporting information Figure S2); the highest amount occurring during the period "RI" (2,071 mm) followed by "RI + FHH" (1837 mm) and "before" (1789 mm). Maximum daily precipitation occurred during the time period "RI + FHH" (103 mm) followed by "RI" (97 mm) and "before" (74 mm). The number of events with three or more days with precipitation was higher during the time period "RI" (18 events), but equal between the other two time periods (11 events). Conversely, the two longest rain events occurred during the time period "RI + FHH" and "before" (34 and 32 consecutive days with precipitation, respectively) compared to the time period "RI" (25 days).

The median and maximum monthly specific discharge among sites was slightly higher during the time period "before" and relatively similar afterward. For the time period "before" the median and maximum monthly specific discharge ranged between 0.06 and 0.21 $m^3\ s^{-1}\ km^{-2}$ and between 0.07 and 0.23 $m^3\ s^{-1}\ km^{-2}$, respectively; for the time period "RI" between 0.03 and 0.11 $m^3\ s^{-1}\ km^{-2}$ and between 0.03 and 0.12 $m^3\ s^{-1}\ km^{-2}$; for the time period "RI + FHH" between 0.04 and 0.19 $m^3\ s^{-1}\ km^{-2}$ and between 0.04 and 0.22 $m^3\ s^{-1}\ km^{-2}$, respectively. However, the standard deviation of monthly specific discharge among time periods across sites was similar and ranged between 0.03 and 0.21 $m^3\ s^{-1}\ km^{-2}$, 0.04 and 0.19 $m^3\ s^{-1}\ km^{-2}$, and 0.03 and 0.18 $m^3\ s^{-1}\ km^{-2}$ for the time periods "before," "RI," and "RI + FHH," respectively.

Our first question was whether the road crossings led to an increase in fine sediment below the stream crossings, before implementation of road improvement or forest harvest and hauling. We used paired upstream/downstream samples collected simultaneously. Since only the increase in sediment in the downstream relative to the upstream sample was of interest, these statistical tests assumed a directional alternative hypothesis. In addition, preliminary assessments of these data found that the difference between the matched pairs did not follow a normal probability distribution and included extreme outliers. Therefore, we used a one-sided Wilcoxon signed rank paired test with continuity correction [*Bauer*, 1972; *Hollander and Wolfe*, 1973]. We tested the hypothesis that the median of differences in turbidity (NTU) or SSC (mg L^{-1}) between locations (below-above) was equal or lower than a given threshold (C). A nonparametric confidence interval and an estimator for the pseudomedian of the difference between locations was also computed [*Bauer*, 1972; *Hollander and Wolfe*, 1973]. We used this approach because central tendency descriptors of magnitude are commonly reported in the literature and are easy to calculate [e.g., *EPA*, 2006; *NCASI*, 2009; *Arismendi et al*., 2013]. Often they are used as management goals and to define regulatory thresholds [*EPA*, 2006; *NCASI*, 2009].

Given the high variability of biological responses to increases in turbidity and SSC across studies (supporting information Table S1) and the possible policy relevance of this study, we did not try to identify a specific threshold of increase in NTU or SSC, but instead present our findings against a range of thresholds that may be more informative than looking at just one threshold. These thresholds (C) (Table 2 and supporting information Table S1) have been identified in the literature as potential values above which high-biological activity or water quality can be impaired. For illustrative purposes in the figures, we note a possible threshold as

Table 2. For This Comparison of Our Responses Against Multiple Threshold Levels, We Tested the Hypothesis That the Median of Differences in Turbidity or SSC Between Sampling Locations (Below Road-Above Road) was Equal or Lower Than a Given Threshold *C*, Where *C* Has Units Either NTU or mg L^{-1}[a]

Metric	Time Period	Site (Below-Above)	$C = 0.2$	$C = 1$	$C = 3$	$C = 5$	$C = 10$	Flow <80th Percentile ($C = 3$)	Flow >80th Percentile ($C = 3$)
Turbidity (NTU)	Before	GUS3	NA	NA	NA	NA	NA	NA	NA
		PH2	1	1	1	1	1	1	1
		Reference PH3[b]	0.973	1	1	1	1	1	1
		PH4	1	1	1	1	1	1	0.712
		UM2	**0.002**	1	1	1	1	1	1
	RI	GUS3	0.726	1	1	1	1	1	1
		PH2	**<0.001**	1	1	1	1	1	1
		reference PH3[b]	**<0.001**	0.068	1	1	1	1	0.905
		PH4	**0.031**	0.977	1	1	1	1	1
		UM2	0.296	1	1	1	1	1	1
	RI + FHH	GUS3	**0.002**	0.974	1	1	1	1	1
		PH2	0.287	1.000	1	1	1	1	1
		reference PH3[b]	**<0.001**	**<0.001**	**<0.001**	**<0.001**	1	**<0.001**	**<0.001**
		PH4	**0.001**	**0.008**	0.234	0.865	1	0.519	0.245
		UM2	1	1	1	1	1	1	1
SSC (mg L^{-1})	Before	GUS3	NA	NA	NA	NA	NA	NA	NA
		PH2	1	1	1	1	1	1	1
		reference PH3[b]	0.697	0.846	0.974	0.997	1	1	1
		PH4	1	1	1	1	1	1	0.92
		UM2	**<0.001**	**0.005**	0.363	0.923	1	1	1
	RI	GUS3	0.999	1	1	1	1	1	1
		PH2	**<0.001**	**<0.001**	0.617	1	1	1	1
		reference PH3[b]	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.819	1	1
		PH4	0.301	0.576	0.952	0.999	1	0.905	0.924
		UM2	**0.000**	**0.049**	1	1.000	1	1	1
	RI + FHH	GUS3	**0.001**	**0.032**	0.573	0.963	1	1	1
		PH2	**<0.001**	**<0.001**	0.336	0.981	1	1	1
		reference PH3[b]	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	1	**0.04**
		PH4	0.765	0.779	0.813	0.855	0.936	0.35	0.22
		UM2	1	1	1	1	1	1	1

[a]We calculated one-sided Wilcoxon signed rank test and used continuity correction of the median difference in turbidity and SSC between paired samples above and below the road crossing at five exploratory threshold levels (*C*); *P* values from the signed rank test are shown for each site and each threshold. Threshold level $C = 0.2$ is the minimum level of detection for our methods. Given the high variability of biological responses to increases in turbidity and SSC across studies (supporting information Table S1), we used multiple thresholds that may be more informative than looking at just one single value. We interpret differences at threshold $C = 3$ (i.e., median difference was 3 NTU or 3 mg L^{-1}) as possibly representing biological significance. Threshold of $C = 3$ was also evaluated during low/medium and high-flow periods. Low/medium flow period occurred when flow was lower than 80th flow percentile of each respective time period. High-flow period occurred when flow exceeded the 80th flow percentile. Time periods are before road improvement (before), after road improvement (RI), and after road improvement + forest harvest + hauling (RI + FHH). See detailed results in supporting information Table S2.

[b]PH3 was not harvested; the road was not upgraded and received no hauling.

an increase of 3 NTUs or 3 mg L^{-1} SSC, although neither has been shown to exert a biological effect on studied species according to available scientific literature (supporting information Table S1).

We performed additional analysis of differences in turbidity and SSC within a site and separated the data into two hydrologic periods that represented high and low/medium flow periods. We defined a "low/medium flow period" to occur when flow values were lower than the 80th flow percentile of each respective time period. A "high-flow period" occurred when flow values exceeded the 80th flow percentile. The magnitude of the 80th flow percentile among sites (mean $\pm$ SD) was relatively comparable across seasons (before: 0.19 ± 0.13 m^3 s^{-1} km^{-2}; RI: 0.13 ± 0.15 m^3 s^{-1} km^{-2}; RI + FHH: 0.16 ± 0.1 m^3 s^{-1} km^{-2}). Using this approach, we examined whether the road crossings led to increased fine sediment in the downstream site sunder specific circumstances (low-flow or high-flow period). We performed all of these statistical analyses using the package "stats" in R ver. 2.15.1 [*R Development Core Team*, 2012].

We addressed our second question, which asks how frequently fine sediment increased downstream of each road crossing compared to upstream, by using a simple frequency analysis of paired turbidity and SSC values. For each site and time period, we computed the difference of each paired below and above road sample for turbidity or SSC and then, sorted the resulting differences from the largest to the smallest (hereafter paired differences). From the total number of paired samples for turbidity or SSC, we calculated the proportion that exceeded each paired difference (hereafter proportion exceeded). We produced a plot of paired differences for each site and time period where the *Y* axis represented the paired differences and the *X* axis the proportion exceeded. When we identified tied values from the paired differences we used the median of the associated proportion exceeded.

Lastly, to examine whether fine sediment concentrations in streams were associated with the amount of discharge, we used a Pearson's product-moment between turbidity and specific discharge, and between SSC and specific discharge. For this analysis we only selected background locations above road crossings that were unaffected by changes in either roads or forest management as these features may differentially affect their hydrology. Similarly, to examine the strength of the relationship between turbidity and SSC at background locations above road crossings, we used the coefficient of determination (r^2). We considered a strong association to exist when $r^2 > 0.5$ [*Moriasi et al*., 2007].

4. Results

4.1. Median SSC and Turbidity Above and Below Road Crossings

Contrary to our original hypothesis, road construction and forest harvest and hauling did not result in significantly higher median suspended sediment or turbidity downstream compared to upstream of the road crossings at these sites (Table 2; Figures 2 and 3; supporting information Table S2). In our comparison of different thresholds in sediment concentrations (turbidity and SSC), we observed only minor and nonsignificant increases in median values after road improvement and forest harvest and hauling. Unexpectedly, there were significant increases in median SSC at the reference site PH3 for the time period "RI" and for both turbidity and SSC for the time period "RI + FHH". The number of sites where we found significant increases in median sediment concentrations increased or decreased depending on the magnitude of a given threshold (Table 2). For example, when we increased the threshold from the reference value $C = 3$ to $C = 5$ for both turbidity (NTU) or SSC (mg L^{-1}) there were no changes in our findings, and when the threshold increased from $C = 3$ to $C = 10$, there was a significant increase in SSC only at the reference site PH3 for the time period "RI + FHH". Conversely, when we decreased the threshold from $C = 3$ to $C = 1$ or from $C = 3$ to $C = 0.2$ (level of uncertainty for the measurement) the number of sites where we found significantly higher sediment concentrations below the road crossing increased (up to three of the five sites). Furthermore, under both "high" and "low/medium" flow periods (Table 2) there was a road effect at the reference site PH3 for turbidity and SSC during the time period "RI + FHH". We also found a road effect on SSC for the same time period at PH3, but only under "high-flow" conditions.

4.2. Frequency of Higher SSC and Turbidity Below Road Crossings

In answer to our second question about how frequently does downstream fine sediment transport occur (Figures 4 and 5; supporting information Figure S2), we found that when the differences between the locations below and above exceeded or were below than the measurement uncertainty (defined as $C = \pm 0.2$),

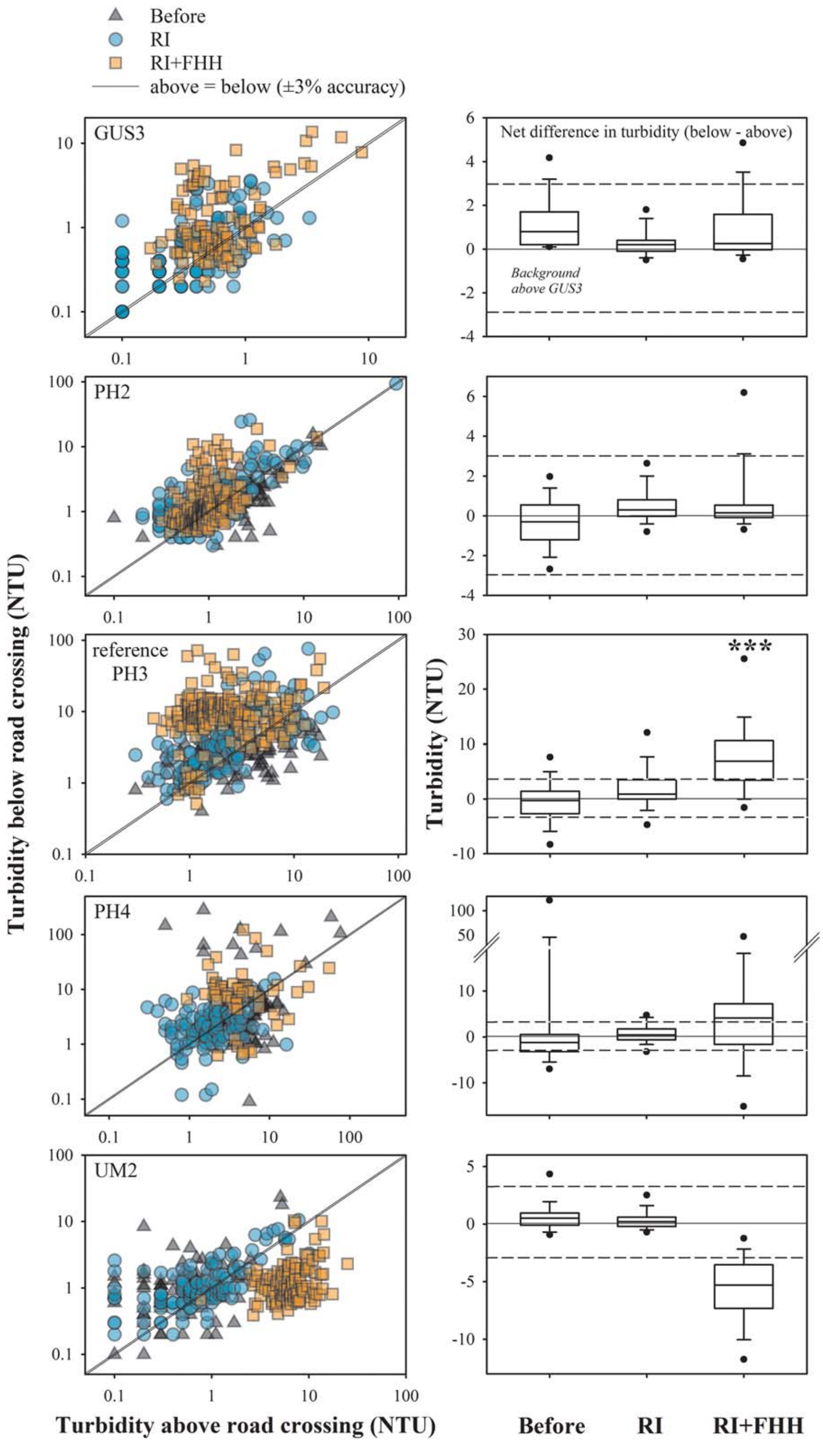

Figure 2. (left) Turbidity (NTU) above the road versus location below the road crossing for each paired sampled, site, and time period. (right) Boxplots (circles represent 5th and 95th percentiles) of differences between locations above and below for each site and time period. *** denotes statistically significant *P values* <0.001. We adopted $C = 3$ (dotted line) as a possible threshold of significant biological response. Time periods included before road improvement (before), after road improvement (RI), and after road improvement + forest harvest + hauling (RI + FHH). GUS3 did not have "before" samples because the road was new construction. The reference site PH3 was not harvested; the road was not upgraded and received no hauling. See detailed results in supporting information Table S2.

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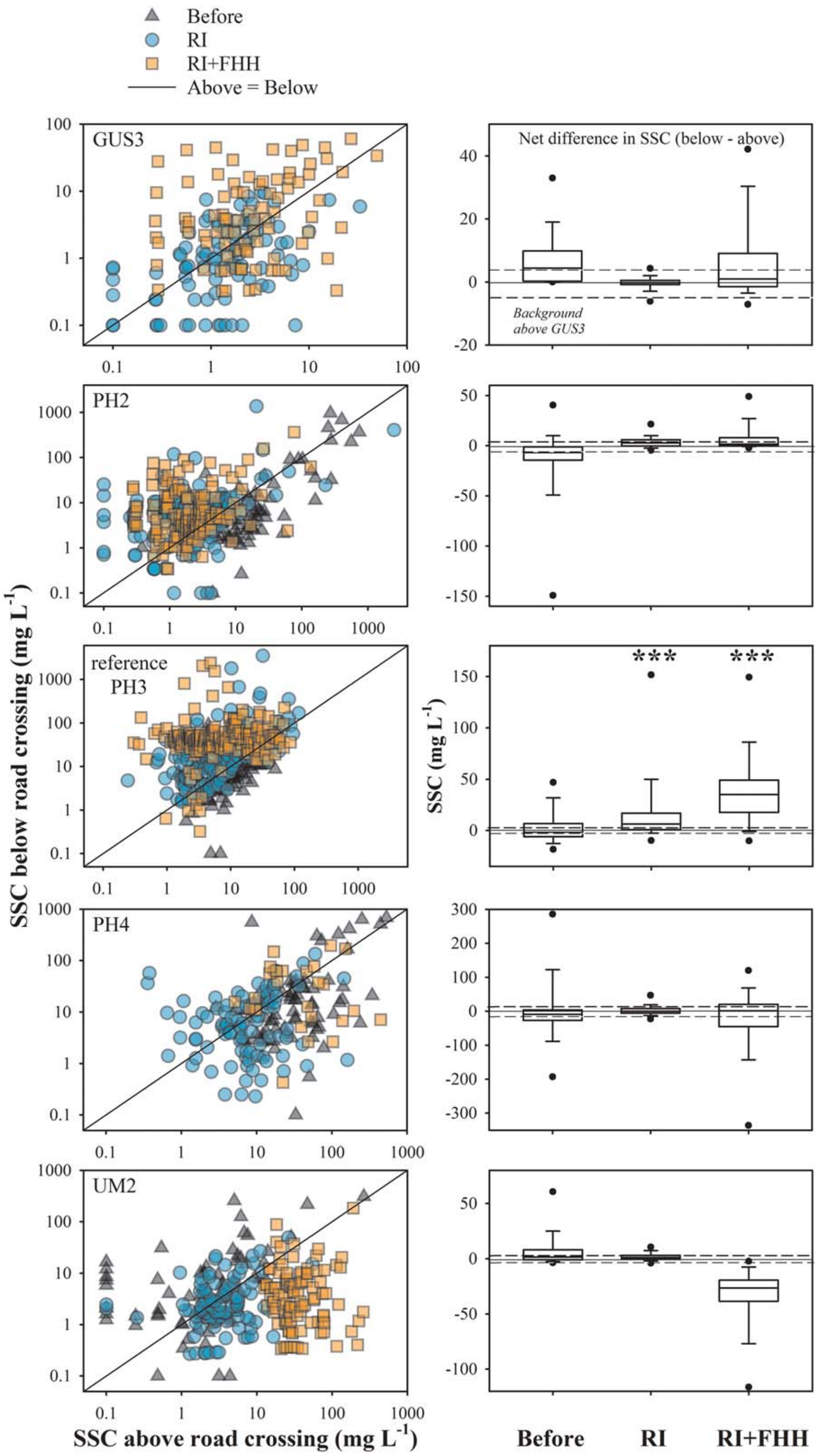

Figure 3. (left) Suspended sediment concentration (SSC; mg L^{-1}) at the location above versus location below the road crossing for each paired sampled, site, and time period. (right) Boxplots (circles represent 5th and 95th percentiles) of differences between locations above and below for each site and time period. *** denotes statistically significant *P values* <0.001. We adopted $C = 3$ (dotted line) as a possible threshold of significant biological response. Time periods included before road improvement (before), after road improvement (RI), and after road improvement + forest harvest + hauling (RI + FHH). GUS3 did not have "before" samples because the road was of new construction. The reference site PH3 was not harvested; the road was not upgraded and received no hauling. See detailed results in supporting information Table S2.

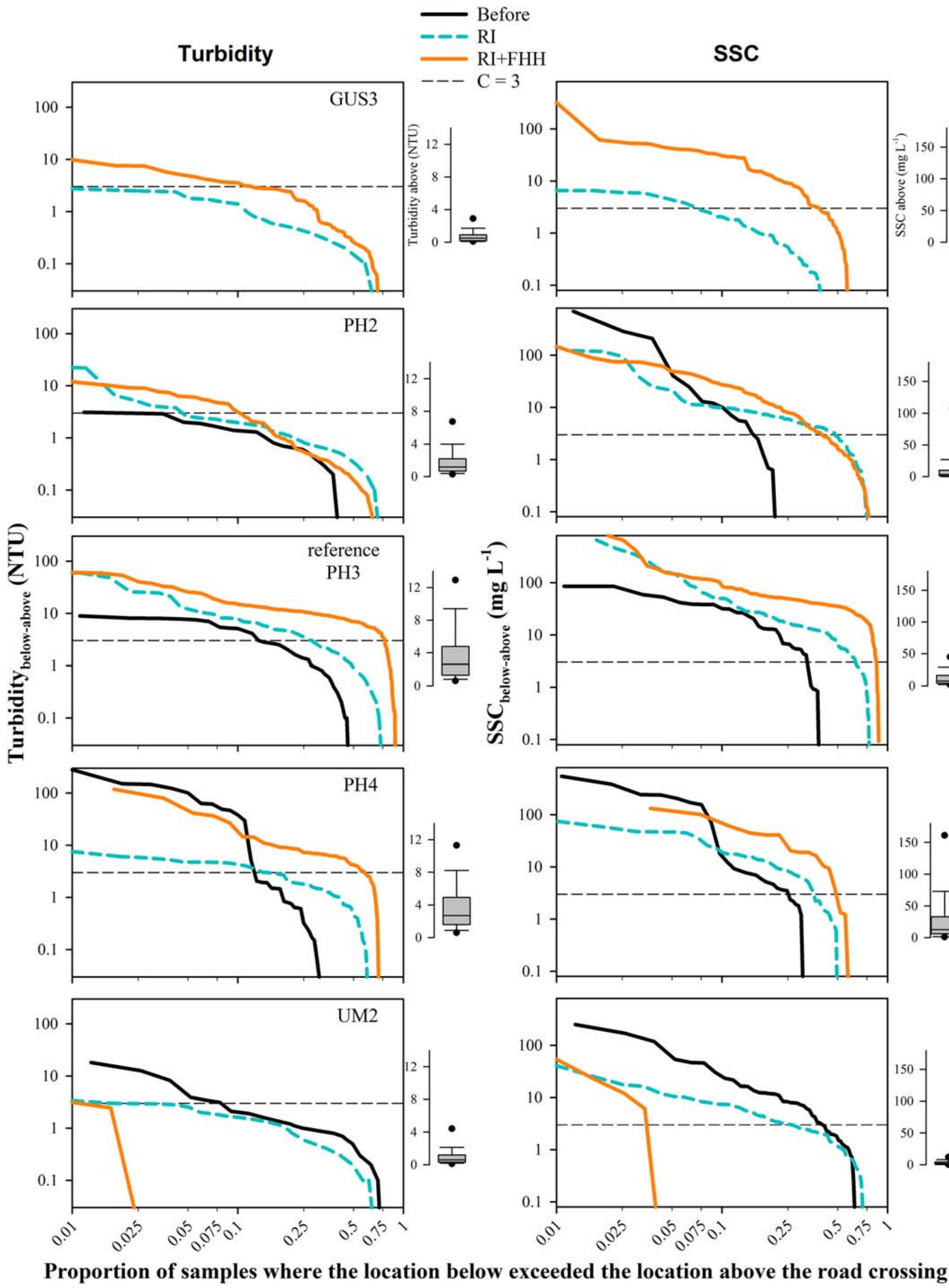

Figure 4. Proportion of samples for which a specified difference between location below and above (left plot for turbidity; right plot for SSC) is equaled or exceeded. Individual graphs represent each site including the three time periods. We adopted $C = 3$ (dotted line) as a possible threshold of significant biological response. Time periods included before road improvement (before), after road improvement (RI), and after road improvement + forest harvest + hauling (RI + FHH). Boxplots (circles denote 5th and 95th percentiles) to the right of plots represent the range of background conditions unaffected by road improvements and forest harvest at each site (before and RI). The reference site PH3 was not harvested; the road was not upgraded and received no hauling.

the percentage of paired samples varied over time (see numbers expressed as proportion in the *X* axis of Figure 4). For example, 46 ± 19% (average among sites ± SD) and 59 ± 19% of the paired samples had higher turbidity and SSC, respectively, at the location above than the location below during the time period "before" (when $y = -0.2$ in Figure 4). At all sites, except in UM2, these values decreased during the next two time periods (21 ± 8% for turbidity and 32 ± 14% for SSC during the time period "RI"; 32 ± 37% and

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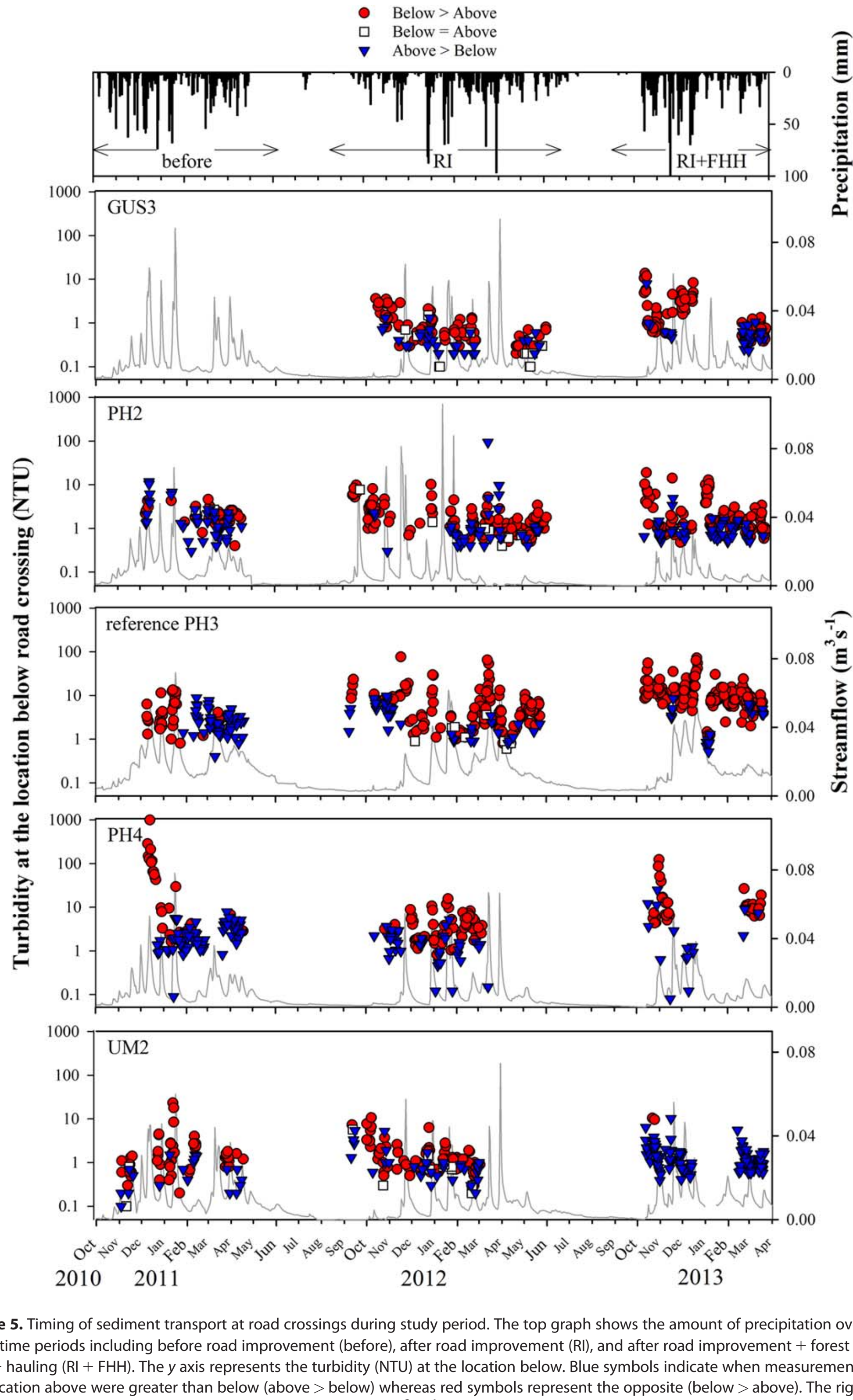

Figure 5. Timing of sediment transport at road crossings during study period. The top graph shows the amount of precipitation over the three time periods including before road improvement (before), after road improvement (RI), and after road improvement + forest harvest + hauling (RI + FHH). The *y* axis represents the turbidity (NTU) at the location below. Blue symbols indicate when measurements at the location above were greater than below (above > below) whereas red symbols represent the opposite (below > above). The right *y* axis for the bottom graphs represents average daily discharge ($m^3 s^{-1}$), calculated using downstream flumes. The reference site PH3 was not harvested; the road was not upgraded and received no hauling. Results for suspended sediment concentration are included in supporting information Figure S2.

Table 3. To Compare Site-Specific Background Relationships Between Suspended Sediment and Discharge, We Calculated Correlation Coefficients Between Turbidity (NTU) and Specific Discharge ($m^3 s^{-1} km^{-2}$), and Between SSC ($mg L^{-1}$) and Specific Discharge ($m^3 s^{-1} km^{-2}$) Using Pearson Product Moment Correlations[a]

		Turbidity			SSC		
Location	Site	r^2	*n*	*P* value	r^2	*n*	*P* value
Above	GUS3	0.06	136	**<0.01**	0.03	136	**0.03**
	PH2	0.01	175	0.64	0.02	175	0.09
	Reference PH3[b]	0.11	173	**<0.01**	0.01	173	0.86
	PH4	0.10	206	**<0.01**	0.16	206	**<0.01**
	UM2	0.04	137	**0.03**	0.01	137	**<0.01**

[a]For this analysis, only data from above road crossing was used, for the periods of "before" road intervention and after road improvement (RI).
[b]PH3 was not harvested; the road was not upgraded and received no hauling.

41 ± 34% during the time period "RI + FHH"). In addition, 43 ± 15% (turbidity) and 38 ± 18% (SSC) of the paired samples represented conditions when the location below exceeded the location above during the time period "before" (when $y = 0.2$ in Figure 4). These values increased at all sites, except in UM2, during the next two time periods (56 ± 9% for turbidity and 60 ± 19% for SSC during the time period "RI"; 53 ± 32% and 55 ± 32% during the time period "RI + FHH", respectively).

We found that when the differences between the locations below and above exceeded a previously defined threshold for turbidity or SSC ($C = 3$) the percentage of paired samples ranged from 0% to 85% (Figure 4). During the time period "RI + FHH", GUS3, PH4, and reference site PH3 had the highest percentage of samples exceeding this threshold (38% for SSC, 58% for turbidity, and 85% for SSC, respectively). We observed a consistent increment in the percentage of paired samples that exceeded this threshold from 7% to 38% between "RI" and "RI + FHH" at GUS3 (SSC) and from 13% to 77% between "before" and "RI + FHH" at PH3 (turbidity). Interestingly, at UM2 the highest percentage of samples exceeding the threshold $C = 3$ occurred during the time period "before". In other cases, such as for PH4 and PH2 (SSC), the largest differences between locations above and below occurred only during the time period "before". Overall, we observed relatively low turbidity and SSC values at background locations ranging between 0 and 12 NTU (up to the 95% percentile) and between 0 and 180 mg L^{-1} (up to the 95% percentile) respectively.

4.3. Relations Between SSC, Turbidity and Specific Discharge

Specific discharge was positively associated with SSC only in some cases (Table 3 and Figure 6). Pearson's correlation coefficients between turbidity and specific discharge were statistically significant, but weak for the upstream sites GUS3 and UM2, and nonsignificant for site PH2. There were similar significant, but weak associations between SSC and specific discharge for upstream sites of GUS3, and UM2 and nonsignificant associations for sites PH2 and PH3. We noticed that at the reference site PH3 this relationship was statistically significant for turbidity and nonsignificant for SSC.

Similar to the relationship between specific discharge and turbidity and between specific discharge and SSC, there was a lack of coherence and a high amount of variability in the strength of the association between turbidity and SSC at locations above road crossing during the time periods before forest harvest and hauling and after road improvement, even though all relationships examined were statistically significant (Table 4). Because locations above roads, during the first two time periods ("before" and "RI"), represent background conditions, unaffected by changes in either road or forest management, we expected that these locations would show the most consistent associations between turbidity and SSC. Contrary to our prediction, only PH4 and GUS3 show no change over time in the strength of the association between turbidity and SSC. In particular, there was a consistent, but weak association between turbidity and SSC over the two time periods at GUS3. For the majority of cases, the strength of these associations was highly variable over time. However, for a few sites, the strength of this association increased (PH2 and UM2) or decreased (PH4 and PH3) across the two time periods before forest harvest and hauling.

5. Discussion

We detected negligible increases in median SSC and turbidity below road crossings after treatment, which included a site with new road construction and three sites with road upgrades followed by forest harvest

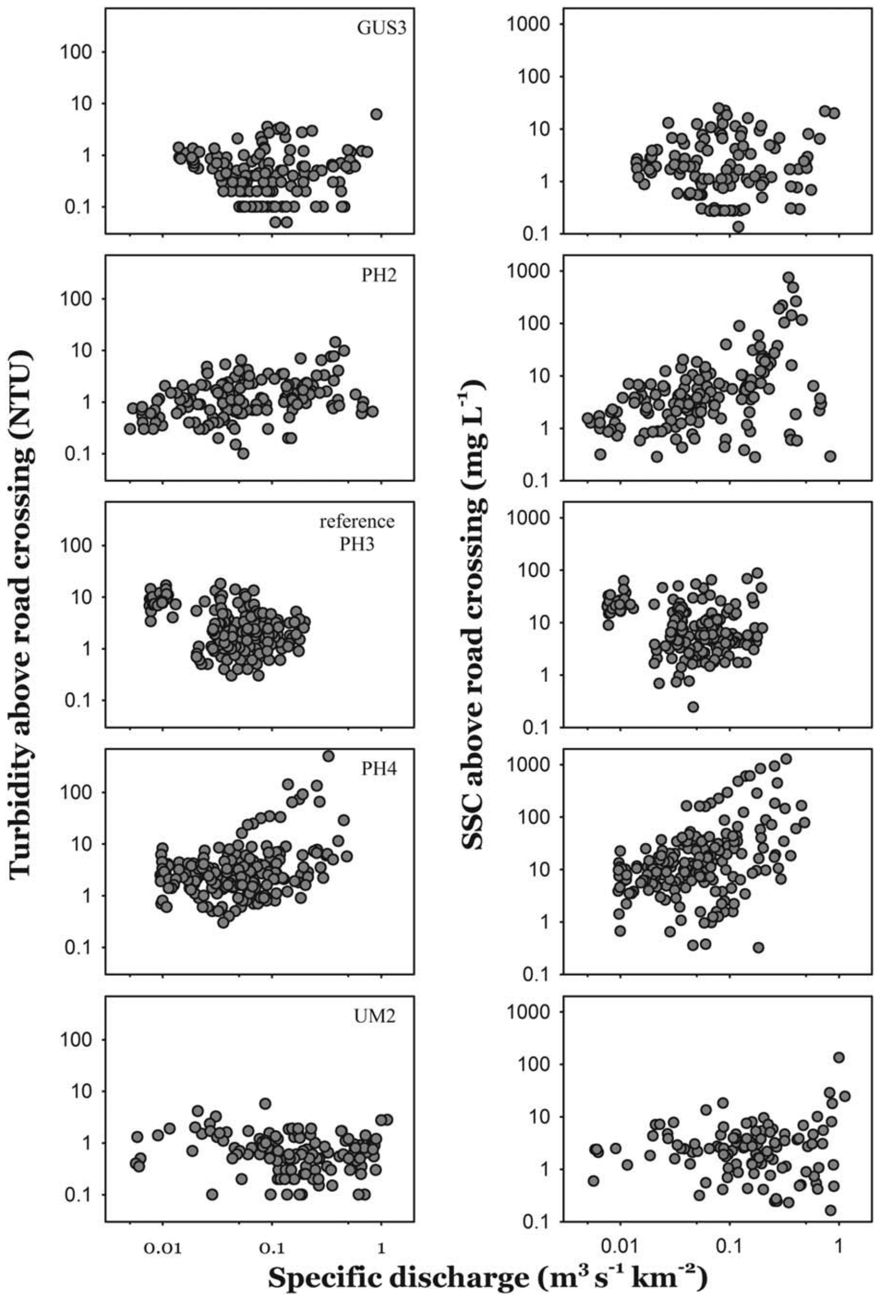

Figure 6. (left) Specific daily discharge ($m^3\ s^{-1}\ km^{-2}$) versus turbidity (NTU) and (right) suspended sediment concentration (SSC mg L^{-1}) at each site. We considered only the sites above road crossings during the time periods before road improvement (before) and after road improvement (RI) as indicative of unaffected by road improvements and forest harvest and hauling. The reference site PH3 was not harvested; the road was not upgraded and received no hauling.

and hauling. Unexpectedly, the reference site showed the highest increases compared to the others. The magnitude of change in suspended sediment concentrations after road improvements, forest harvest and hauling in the treatment sites was small and likely had minimal biological relevance (see literature review about biological responses to fine sediment in supporting information Table S1). The small increases in fine-suspended sediment concentrations at the reference site highlight the importance of local factors, and suggest that stream-adjacent disturbance events may contribute sediment similarly to road crossings. Further, regression models that predicted SSC from either flow or turbidity differed in their performances spatiotemporally. Below, we provide our insights about the effects of current forest road management practices on

Table 4. To Compare Site-Specific Correlations Between Turbidity (NTU) and SSC (mg L^{-1}) for Above Road Locations, We Calculated Pearson Product Moment Correlation Coefficients Before Road Intervention ("Before") and After Road Improvement ("RI")[a]

		Before		RI	
Location	Site	r^2	*n*	r^2	*n*
Above	GUS3	0.34	68	0.38	131
	PH2	0.48	89	**0.96**	187
	reference PH3[b]	**0.84**	92	0.45	176
	PH4	**0.74**	100	**0.62**	106
	UM2	0.40	95	**0.61**	124

[a]Values of $r^2 > 0.5$ are in bold. *P* values for all comparisons <0.001.
[b]PH3 was not harvested; the road was not upgraded and received no hauling.

suspended sediment and turbidity in these sites as well as considerations for future research. We also describe and discuss an alternative approach to standards and thresholds, using comparisons of multiple thresholds as potential indicators of biological relevance.

5.1. Contemporary Forest Road Practices and Fine Sediment Concentrations Above and Below Road Crossings

Our findings of minimal increases in turbidity and SSC below road crossings contrasted with previous studies that documented larger and consistent increases in suspended sediment in streams after road construction/improvement and hauling [e.g., *Brown and Krygier*, 1971; *Beschta*, 1978; *Wooldridge*, 1979; *Reid and Dunne*, 1984; *Bilby et al*., 1989]. In the past, road drainage systems were designed to route water and the sediment it carried off the road and into a ditch and then to a stream as efficiently as possible. This practice has changed dramatically over the last several decades with the goal now being to route forest road runoff to the forest hillslopes and not to the stream. The location, construction, maintenance, and especially the lack of hydrological connectivity have been shown to contribute to disconnecting streams from road-related erosive processes [*Luce and Black*, 1999; *Croke et al*., 2005]. Forest management practices of diverting water off roads using water bars, moving sediment-laden water to depositional areas where water infiltrates into the soil, reducing sediment transport with sediment traps that dissipate energy, and installing relief culvert outlets are now more commonly used [*Keller and Sherar*, 2003; *Croke et al*., 2005; *Reiter et al*., 2009; *Wear et al*., 2013]. Moreover, the use of less erosive surfacing material in roads has been promoted to minimize wet weather hauling impacts near streams [*Keller and Sherar*, 2003]. In the Pacific Northwest of United States, improvements in road construction and maintenance appear to be linked to recent trends of declining turbidity over time [*Reiter et al*., 2009] and lower sediment yield in streams [*Zégre*, 2008].

In our study, the reference road crossing in the unharvested watershed with no road upgrades and no hauling unexpectedly had higher median concentrations of suspended sediment and turbidity than all other study sites. This site was not the most hydrologically connected to the road, which suggests that, in some cases, hydrological connectivity may not necessarily be the best predictor of changes in sediment concentrations. We observed an exposed tree root-wad within the stream channel between PH3a and PH3b following a wind-throw event during the time period "RI". This minor disturbance provided additional information about possible source of fine sediment (see photographs in supporting information Figures S3–S6). It is likely that during the high-flow season, the exposure of tree roots retaining soil in the stream channel contributed to increased suspended sediment downstream. Collectively, our findings suggest that local disturbances could influence suspended sediment in low order streams as much or more than road maintenance. Local disturbances are frequent and they affect sediment delivery to streams during stochastic processes driven by climatic and other discrete events in time and space [*Grant and Wolff*, 1991; *Benda and Dunne*, 1997; *Benda et al.*, 2004].

After treatment, the magnitude of increased sediment transport due to road crossings compared to above roads seems to be minimal (less than four units of turbidity or SSC; supporting information Table S2), but it is also consistent over time as is shown in our analysis of exceedances. Indeed, higher turbidity and SSC at the downstream location, compared to the upstream location, is more frequent after treatment in several of the sites. This could be influenced by the increased connectivity and larger watershed area of the downstream site as well as channel morphology at these sites. Because our study sites show naturally low turbidity and minimal changes in SSC local factors can be of high importance in determining the fine sediment concentrations in the water. In addition, it is important to evaluate changes in concentration within the context of the magnitude of measurements and the accuracy of methods (e.g., if 3 and 100 NTU represent the baseline information from two different streams, then differences of ±0.09 and ±3 NTU would not be detectable due to 3% of accuracy in methods, respectively). Moreover, the specific thresholds at which excess suspended sediments are harmful to biota are still unclear (see discussion about biological implications below) and the decision about which threshold should be used is a societal and political decision; our findings illustrate a way to evaluate multiple thresholds for future decision makers.

5.2. Relationships Between SSC, Discharge, and Turbidity

Our findings showed weak relationships between discharge and SSC, between discharge and turbidity, and inconsistent associations between turbidity and SSC during the two time periods before forest harvest and hauling. There are many studies that have used discharge to estimate SSC [e.g., *Walling*, 1977; *Reid and Dunne*, 1984; *Williams*, 1989]; however, there are concerns about the extensive use of this relationship due to the high variability of sources, travel time, storage, and availability of sediment over time [*Walling*, 1977; *Williams*, 1989; *Major et al.*, 2000; *Nistor and Church*, 2004]. An earlier study conducted on small streams in Oregon reported large year-to-year variation in the relationship between discharge and SSC [*Brown and Krygier*, 1971]. Furthermore, we illustrated that although the association between turbidity and SSC could be statistically significant, it can also be weak [e.g., *Reiter et al.*, 2009] and both time and site dependent [e.g., *Gippel*, 1995; *Meadows*, 2009]. Significant and positive associations between turbidity and SSC have been previously documented [*Kunkle and Comer*, 1971; *Lewis*, 1996; *Uhrich and Bragg*, 2003; *Zégre*, 2008; but see *Henley et al.*, 2000; *Nistor and Church*, 2004]. However, changes in the relationship between turbidity and SSC at higher turbidities [*Lane and Sheridan*, 2002] and hysteresis during both individual storms [*Pfannkuche and Schmidt*, 2003] and through a season [*Paustian and Beschta*, 1979] have also been reported. For example, the first storm after the dry season has been reported as an important event of fine sediment delivery because dry sediment and summer dust can be transported in the initial flush of rain, which leads to higher turbidities than subsequent storms of similar magnitude [*Paustian and Beschta*, 1979] resulting in hysteresis where the fine sediment delivery depends not only on current storms, but also on past events of discharge. Hysteresis may also occur during individual storms when the concentration of fine sediments or turbidity could be higher at similar magnitudes of discharge during the rising limb of the hydrograph than during the falling limb [*Williams*, 1989; *Nistor and Church*, 2004]. Hysteresis could be associated with changes in particle size distributions over time where at the same SSC value turbidity sensors would be more sensitive to small particle than large particle sizes [*Gippel*, 1995; *Lewis*, 1996]. Thus, the inconsistent associations between turbidity and SSC in our findings suggest that they can be measuring suspended particles with differing sensitivity to size, concentration, and storm conditions. In this context, the ratio of SSC against turbidity could be explored as an indication of changes in particle size due to road construction/improvements and forest management. Nevertheless, we suggest that in some cases, the extended use of sediment rating curves based on discharge and turbidity relationships over single time periods or sites may provide unstable or unreliable predictions of suspended sediment yields in small streams.

5.3. Biological Implications

Fine-suspended sediment is one of the most difficult potential stressors to quantify for aquatic life, because biological responses are both site, season and species specific [e.g., *Wood and Armitage*, 1997; *Newcombe and Macdonald*, 1991; *Henley et al.*, 2000; others in supporting information Table S1]. The literature shows a variety of biological responses for different turbidity and SSC values (several examples are contained in supporting information Table S1). However, determining thresholds of impact from the literature is challenging. Turbidity values above 25 NTU, and SSC above 6000 mg L^{-1} have been shown to decrease primary production up to 50% [*Lloyd et al.*, 1987]; alternatively, in other studies, increases in turbidity from 5 to 10 NTU were suggested to reduce the biomass of periphyton and macrophytes [*Parkhill and Gulliver*, 2002]. Macroinvertebrate communities in streams may show changes in their species composition when SSC increases more than 30% [*Angradi*, 1999]. At higher trophic levels, there are also a broad range of biological responses to increased turbidity (supporting information Table S1). There was a reduction in population size of Brown Trout in conditions 1040 mg L^{-1} SSC [*Herbert et al.*, 1961]. Also, Coho Salmon were observed to avoid areas when turbidity exceeded 70 NTU or 88 and 100 mg L^{-1} SSC [*Bisson and Bilby*, 1982], but food consumption only decreased above 4000 NTU [*Bonner and Wilde*, 2002]. In other studies, Cutthroat Trout and Coho Salmon reduced drift prey captures at 50 NTU, but benthic feeding success was still about 70% at 100 NTU compared to 0 NTU [*Harvey and White*, 2008]. Above 400 NTU neither species were feeding. Reactive distance of Rainbow Trout at 15 NTU and 30 NTU are reduced to 80% and 45%, respectively, of reactive distance under baseline conditions [*Barrett et al*., 1992] and 60 NTU pulses reduces reactive distance from 30 to 10 cm [*Berg and Northcote*, 1985].

It is important to consider that turbidity and SSC may affect species and ecosystems through different processes and therefore they may need to be considered independently. For example, turbidity meters may be more responsive to changes in fine-size particles such as silt and clay. The concentration of fine-size particles can be directly associated to water transparency and thus, primary production (see examples in supporting information Table S1). Conversely, coarser sediment particles (e.g., sand) may not be detected by turbidity meters [*Gippel*, 1995] although they can clog the gravel bed pores resulting in decreasing permeability of the stream bed [*Yamada and Nakamura*, 2009]. Even under low levels of SSC this may result in decreases of the egg-to-fry survival for salmon (supporting information Table S1). Because the variety of impact thresholds in the existing biological literature (supporting information Table S1), we propose evaluating results using a range of thresholds of increased sediment, and in our example, set thresholds as the magnitude of increase below the road, compared to above the road. We recognize the thresholds we evaluated are very low and do not necessarily portray a general biological response threshold value, but this approach provides a general framework that could be adapted for other turbidity or suspended sediment levels of concern by management and regulatory groups across regions and/or taxa. In addition, it is important to consider the frequency and duration of turbidity (or SSC) exceeding background conditions at different flow percentiles (Figure 4). Even though thresholds can be relatively low they could be useful to detect changes under very low turbidity (or SSC) baseline conditions. Collectively, and considering a diverse range of responses of aquatic organisms to fine-suspended sediment, our findings suggest the influence of these road crossings for increasing suspended sediment following contemporary forest management in our study sites are likely of minimal biological relevance.

5.4. Caveats and Considerations for Future Studies

Although this case study had limited replication of road treatments, the findings are comparable to what has been seen in other studies [e.g., *Brown and Krygier*, 1971; *Beschta*, 1978; *Gomi et al*., 2005]. Given the high-spatiotemporal variability and the small magnitude of increases in fine-suspended sediment, it is difficult to make broad generalizations from our findings. For example, differences in geology and physiography of forested watersheds can influence suspended sediment yields [*Bywater-Reyes et al*., 2017]. In addition, differences in precipitation and peak flows among seasons and time periods could influence responses above and below roads or among sites. However, climatic patterns are beyond anyone's control in a pre-post study. Therefore, our study was designed to address whether the road and forest treatments resulted in increased SSC or turbidity within a site below the road compared to above the road and not to try to compare across time periods as a functions of storm magnitude or discharge.

Findings from this field study could have been impacted by several other factors. The upstream site in the period "RI + FHH" could have been affected by suspended sediment associated with forest harvest, potentially swamping the road effect. In addition, similar to most forested areas in the region, our study sites are located in a landscape that has been influenced by historical disturbances (i.e., landslides, fire, and forest harvest) and thus, our background conditions could have been influenced by legacy effects. Our sampling was not as frequent as would have been optimal for both the examination of short-term responses across sites and treatments and for evaluation of the strength of relationships among turbidity, SSC, and discharge at finer temporal scale (e.g., hours or within specific storms).

We recommend that future studies consider several things. In cases when the number of study sites is limited, the use of several locations along the stream channel (see a "false road" approach in *Norman et al*. [2009]) could be useful to account for influences not related to the road presence or forest management practice. Higher frequency sampling could be more effective in comparing differences in duration/magnitude events between reference and treatment conditions [e.g., *Diehl and Wolfe*, 2010] or to quantify the maximum concentrations during an event. We recognize the challenges for higher frequency sampling; SSC is costly to measure frequently [*Davies-Colley and Smith*, 2001] and in-situ turbidity sensors have challenges with field calibration and long-term deployment [*Lewis et al*., 2001]. Higher frequency sampling can be useful to answers questions about the synchrony of short-term events and storm-specific relationships between in situ turbidity and SSC, especially when a more precise estimation of total sediment loads is of main interest [e.g., *Gippel*, 1995; *Lewis*, 1996; *Meadows*, 2009].

Additional descriptors of fine-suspended sediment concentrations might be created to account for biological relevancy (supporting information Table S1). Rather than using only central tendency metrics, it would be informative to evaluate suspended sediment in streams as regimes that include not only duration and magnitude [*Newcombe and Macdonald*, 1991; *Diehl and Wolfe*, 2010], but also timing and variability of events (for examples for streamflow and stream temperature regimes, see *Poff et al*. [1997] and *Arismendi et al*. [2013], respectively). Further, the use of simulation models may be useful to provide a mechanistic view of ecological responses to changes in suspended sediment in streams [e.g., *Harvey and Railsback*, 2009].

6. Conclusions

Our study of effects of forest road improvement and forest harvest found no evidence to suggest that current management practices increased median fine-suspended sediment concentrations in streams above biologically meaningful levels. Turbidity and SSC below road crossings in our studied watersheds appeared to be far less than what was observed in studies under historical forest practices. Rather than using a single threshold to evaluate statistical significance, we evaluated our findings in light of multiple regulatory thresholds and provided an expanded perspective of the potential biological significance of the changes in sediment concentrations. This is important due to the magnitude, frequency and timing of fine sediment concentrations which can be influenced by the variability of factors including discharge, precipitation, but also by site-specific characteristics (e.g., local tree fall and bank erosion) across years. In addition, the results show that using turbidity or discharge to predict SSC is informative only under limited circumstances; relationships between such variables have to be regularly tested at each location across different time periods. Thus, using turbidity or flow to predict SSC must be done with caution. Lastly, when evaluating headwaters that naturally have low turbidity and SSC, local factors can be of high importance in determining the fine sediment concentrations in the water.

Appendix A

The following sources were used to provide a summary of the effects of fine sediments on aquatic organisms (supporting information Table S1):

Berg, [1983]; *Bryce et al.*, [2010]; *Campbell*, [1954]; *Harvey et al.*, [2009]; *Herbert and Richards*, [1963]; *Herbert and Wakeford*, [1962]; *Hughes*, [1975]; *Izagirre et al.*, [2009]; *Langer*, [1980]; *Lawrence and Scherer*, [1974]; *McCabe and O'Brien*, [1983]; *McLeay et al.*, [1987]; *Newcomb and Flagg*, [1983]; *Noggle*, [1978]; *Nuttall and Bielby*, [1973]; *Peters*, [1967]; *Phillips*, [1970]; *Reynolds et al.*, [1988]; *Robertson*, [1957]; *Rosenberg and Snow*, [1977]; *Rosenberg and Wiens*, [1978]; *Scullion and Edwards*, [1980]; *Shaw and Maga*, [1943]; *Sigler et al.*, [1984]; *Slaney et al.*, [1977]; *Smith*, [1939]; *Suchanek et al.*, [1984a]; *Suchanek et al.*, [1984b]; *Tebo*, [1955]; *Turnpenny and Williams*, [1980]; *Updegraff and Sykora*, [1976]; *Wagener and LaPerriere*, [1985]; and *Whitman et al.*, [1982].

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Data sets used in our analyses (supporting information Data Sets S1–S6) are available in the supporting information. Tom Dunne, Fred Swanson, and George Ice provided discussion about ideas and hypotheses. Bob Danehy, Brooke Penaluna, four anonymous reviewers and the Associated Editor provided comments that improved the manuscript. Amy Simmons, Peter James, and Dave Hockman-Wert provided supporting data, and Jon Laine, Michael Thompson, Andrew Yost, Andrew Herstrom, Doug Bateman, Ian Hayes, and Alex Irving assisted in the field. Funded by Oregon Forest Industries Council (OFIC), National Council for Air and Stream Improvement, Inc. (NCASI), Oregon Department of Environmental Quality (ODEQ) Agreement 035–14 and 109–14, Weyerhaeuser Co. Additional indirect support provided by Oregon State University, Oregon Department of Forestry, NCASI, U.S. Forest Service, and Weyerhaeuser Co.

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