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Effects of contemporary forest harvesting on suspended sediment in the Oregon Coast Range: Alsea Watershed Study Revisited

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ABSTRACT

Forest harvesting practices can expose mineral soils, decrease infiltration capacities of soils, disturb the stream bank and channel, and increase erosion and fine sediment supply to stream channels. To reduce nonpoint source sediment pollution associated with forest management activities and to maintain the high water quality typically provided from forests, best management practices (BMPs) were developed and implemented. While BMPs have evolved over time, the effectiveness of contemporary BMPs, particularly for harvesting practices, have not been thoroughly investigated, especially in comparison to historical practices. The objectives of this study were to (1) determine the effects of contemporary harvesting practices on suspended sediment concentrations and yields and (2) examine the legacy effects from historical harvesting on suspended sediment concentrations. The Alsea Watershed Study was an important early research site that lead to the development of contemporary forest management practices to protect water quality and fish habitat in Oregon and elsewhere. By returning to the same watersheds that were harvested in 1966, this is one of the few times that a watershed-scale study is able to directly compare and contrast the effects of historical practices with contemporary practices. The Alsea Watershed Study Revisited includes the same three watersheds as the original study. Flynn Creek (FCG, 219 ha) is an old-growth dominated reference watershed. Deer Creek (DCG, 315 ha) is an extensively managed watershed that was patch-cut during the original study. Needle Branch (NBLG, 94 ha) was clearcut harvested in the original study and again in the recent study, but with contemporary BMPs, including riparian buffers. The upper portion of Needle Branch was harvested in 2009 (Phase I), while the lower portion of the watershed was harvested in 2015 (Phase II). We monitored suspended sediments and discharge from WY 2006–2016, and analyzed this data using multiple linear regression procedures and ANCOVA. Average suspended sediment yields ranged from 55–313 Mg km^{-2} yr^{-1} in FCG, 31–102 Mg km^{-2} yr^{-1} in NBLG, and 69–127 Mg km^{-2} yr^{-1} in DCG. We found no evidence that contemporary harvesting techniques affected suspended sediment concentrations or yields. Overall, suspended sediment concentrations and yields after contemporary harvesting were similar to historical pre-treatment levels.

1. Introduction

Increased suspended sediment concentrations, loads, or yields after forest management activities remain a concern for land managers due to potential degradation of drinking water quality and harmful effects of excessive sediment to many aquatic species, including salmonid fishes (Gomi et al., 2005; Greig et al., 2005; Cristan et al., 2016). Forest operations, such as road building, timber yarding, machine trail development, and slash disposal, can expose mineral soils, decrease infiltration capacities of soils, and increase erosion and fine sediment supply to stream channels (Wemple et al., 1996; Motha et al., 2003; Litschert and MacDonald, 2009). After forest management activities on steep hillslopes, mass movements can result in substantial increases in suspended sediment transport to stream channels (Beschta, 1978). Historical practices conducted without riparian buffers or other stream-protection measures increased the potential for disturbance of stream

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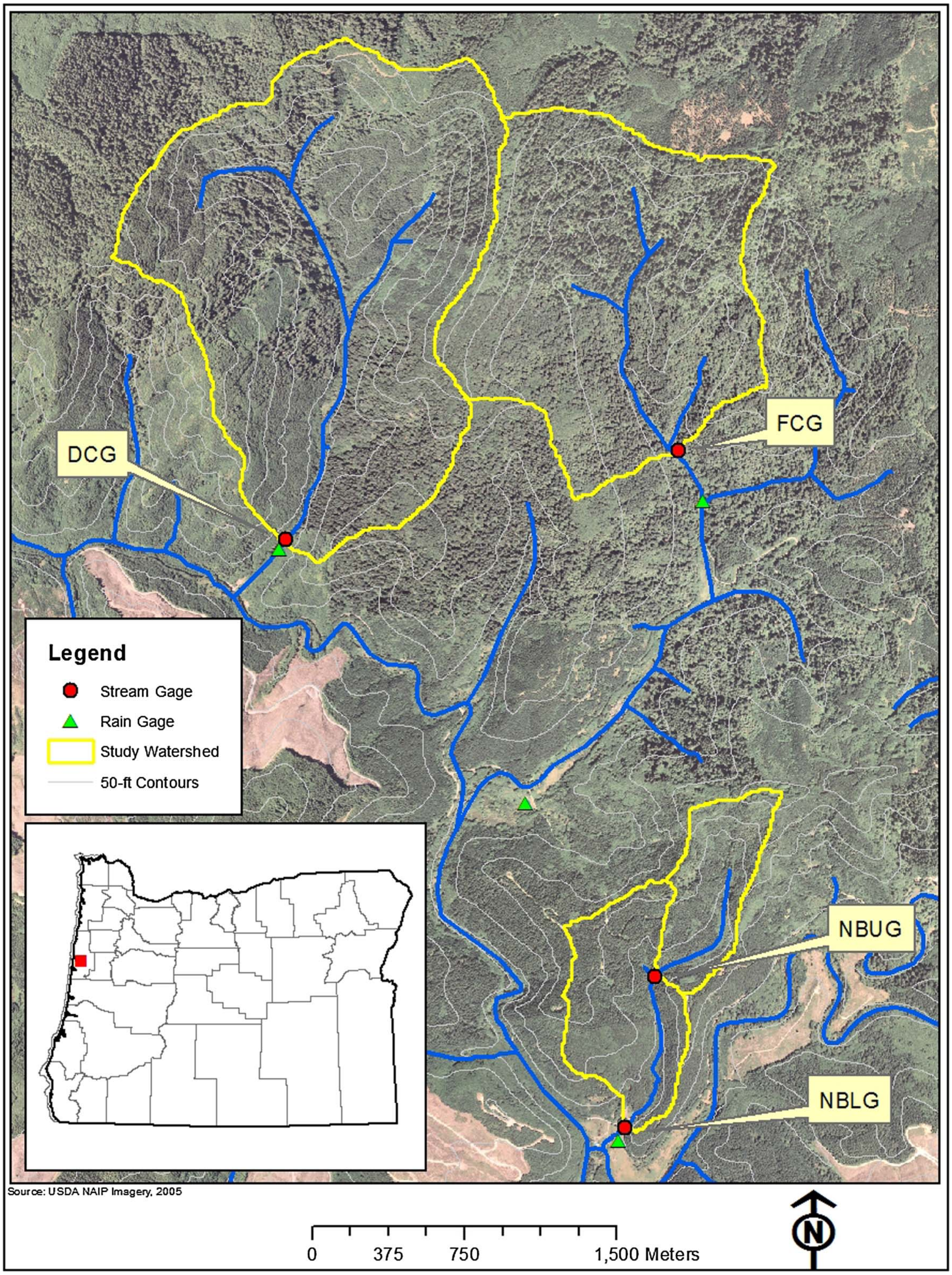

Fig. 1. Overview of study site. Inset shows location of study with the state of Oregon, USA. FCG was the unharvested reference, DCG has been extensively managed since the 1960s, and NBLG and NBUG were clear-cut as part of this study.

banks and channels by both yarding and site preparation practices (Beasley, 1979; Van Lear and Kapeluck, 1989). Harvesting can also change the hydrologic regime and drainage density, which may affect the sediment transport capacity of streams (Croke and Mockler, 2001; Grant et al., 2008).

To reduce nonpoint source pollution associated with forest management activities and maintain the high water quality typically provided from forests, Best Management Practices (BMPs) have been developed and implemented by many individual states (Ice, 2004). However, many questions remain about BMP effectiveness at mitigating nonpoint source pollution to protect beneficial uses of water (Ice et al., 2004; Cristan et al., 2016). Much of the uncertainty is due to contradictory results from different studies, which have included a broad range of forest harvesting practices, harvesting intensities, watershed characteristics (e.g., forest type, soils, geology, climate, and physiography), and applications of BMPs (Aust and Blinn, 2004; Anderson and

Lockaby, 2011; Cristan et al., 2016). For example, many studies have demonstrated a reduction in erosion and sediment delivery to streams with properly applied BMPs, relative to unrestricted harvesting (Keim and Schoenholtz, 1999; Wynn et al., 2000; Hotta et al., 2007; Choi et al., 2014). However, others have observed increases in sediment delivery after forest harvesting, even with BMPs implemented (Arthur et al., 1998; Wear et al., 2013).

In many regions, the perception of the effects of forest harvesting practices on sediment are based on studies that examined land use practices that are outdated and do not accurately reflect contemporary practices. In Oregon, concerns in the 1950 and 1960s about the effects of forest practices on water quality and fish habitat resulted in key paired watershed research at the H.J. Andrews Experimental Forest (Fredriksen, 1970; Fredriksen, 1975; Swanson and Jones, 2002) and the Alsea Watershed Study (Brown and Krygier, 1971; Moring, 1975a; Stednick, 2008). The Alsea study was instrumental in demonstrating that past road construction practices, large harvest areas, and little protection of streams (i.e., retention of forested stream buffers) had the potential to exacerbate the delivery of suspended sediment to streams (Harris, 1977; Beschta, 1978; Beschta and Jackson, 2008). The results from this study influenced the development of regulations for protection of water quality and fish habitat in the 1971 Oregon Forest Practices Act (Hairston-Strang et al., 2008). Unfortunately, investments in forest watershed research have not been sustained across the U.S. and elsewhere as forest practices and operations technologies have advanced rapidly (Stednick, 2008). As such, there are many knowledge gaps regarding the effects of contemporary forest management practices on water quality and aquatic habitat.

The Alsea Watershed Study Revisited provided a unique opportunity to investigate and compare the suspended sediment response to contemporary forest harvesting practices (e.g., retention of riparian vegetation for provision of shade and reduction of sediment delivery and channel disturbance) with the impacts from historical (1960s) harvesting practices (e.g., no riparian vegetation retained, severe bank and channel disturbance, and intense broadcast burning for site preparation). In 1990, the Alsea Watershed Study (AWS) was reactivated to assess long-term responses of the watersheds to commercial forest harvesting (Stednick, 2008). As an extension of the reactivation of the site, a study of forest harvest practices using contemporary BMPs on private timberlands began in 2006. The upper portion of the Needle Branch watershed was harvested in 2009, while the lower portion of the watershed was harvested in 2014 and 2015. Here, we present analysis of suspended sediment concentrations and yields across 11 years, from pre-treatment (WY 2006–2009), post-harvest Phase 1 (WY 2010–2014), and post-harvest Phase 2 (WY 2015–2016). Specifically, the objectives of this research were to address the following questions:

(a) What are the effects of contemporary harvesting practices on suspended sediment concentrations and yields?
(b) Are sediment yields lower from stands managed under contemporary harvest practices relative to historic practices?

2. Methods

2.1. Site description and history

The Alsea Watershed Study Revisited (located at approximately 44.5°N, 123.9°W) was a paired-watershed study (Fig. 1) consisting of a reference watershed (Flynn Creek, 219 ha; measured at the Flynn Creek Gage or FCG) and a nearby treatment watershed (Needle Branch, 94 ha; measured at the Needle Branch Lower Gage or NBLG). Current harvesting practice rules stipulate that harvests be less than 48.5 ha (120 acres) and replanted trees must be "free-to-grow" before nearby harvests are conducted; therefore, the upper half of the treatment watershed, (35 ha; measured at the Needle Branch Upper Gage or NBUG) was harvested in 2009 (Phase I) and the lower half was harvested in the fall of 2014 and mid-summer 2015 (Phase II). Harvests were logged using hand felling and cable yarding systems with no yarding through stream channels. Unlike the original AWS, there was no wood removal from stream channels—any woody material that fell into unbuffered reaches during the operation was left within the stream channel. No new roads were built during the AWS Revisited and most of the roads were along the ridgetop. Existing roads received a fresh application of gravel, any blocked ditches were cleaned, and any needed ditch relief culverts were installed. No riparian buffers were retained on non-fish bearing stream segments of Needle Branch. This included ~969 m of stream segments during the Phase I harvest and an additional ~588 m of stream segments during the Phase II harvest. These non-buffered segments still had machine exclusion protections (total = 1557 m). Riparian management areas (RMAs) of ~15 m widths were retained on fish-bearing stream reaches of Needle Branch. This included ~987 m during the Phase I harvest and an additional ~833 m of stream reaches during the Phase II harvests (total = 1820 m). Unlike the original AWS there was no broadcast burning—harvest – residuals were piled and burned.

A third watershed, Deer Creek (315 ha; measured at the Deer Creek Gage or DCG) was used as a treatment watershed in the original Alsea Watershed Study (roads were built and patch-cut in 1965–1966), and serves as a secondary control for the current study and is used to compare contemporary and historical sediment yields in the discussion section.

The study area is located in the central Oregon Coast Range, a highly-dissected mountainous region characterized by short, steep, soil-mantled hillslopes. In general, the soil textures of these watersheds are loams and gravelly loams on the hillslopes and valley bottoms and clay loams on the ridges. Geology consists primarily of Eocene Tyee Formation sandstone and siltstone. The region has a Mediterranean-like climate with dry summers and wet winters. The mean annual precipitation (1981–2010) of the study region is ~2192 mm (PRISM Climate Group, 2004). Precipitation primarily occurs from October to April in "long-duration, low-to-moderate intensity frontal storms" (Harr, 1976) (see Fig. 2). Snow, while occurring occasionally, does not usually accumulate and is therefore a negligible portion of the precipitation record (Moring and Lantz, 1974).

Flynn Creek is a 2nd-order stream with a mean watershed elevation of 280 m, mean watershed gradient of 33°, and mean channel gradient of 0.025 $m\,m^{-1}$ (Table 1). The catchment, having never received silvicultural treatments or other human perturbations relevant at the watershed scale, was designated a Research Natural Area in 1975 by the USDA Forest Service. At the time of the original Alsea Watershed Study canopy vegetation consists of 75–115 yr-old red alder (*Alnus rubra*) along with a mix of 75–95 yr-old and 115–155 yr-old Douglas-fir (*Pseudotsuga menziesii*) based on information provided in Moring and Lantz (1974). At the time of the original Alsea Watershed Study Brown et al. (1973) estimated the red alder component to be 68% of the forest cover. The channel substrate in FCG primarily consisted of gravels (42.6% ± 0.08 SD) and fines (< 1 mm; 19.1% ± 0.04 SD) with lesser amounts of cobbles, boulders, and bedrock (unpublished data).

Needle Branch is a 2nd-order stream with a mean watershed elevation of 222 m, a mean watershed gradient of 39°, and average stream gradient of 0.014 $m\,m^{-1}$ (Table 1). The catchment was composed of 44 yr-old Douglas-fir occurring primarily on the hillslopes with red alder of the same age-class inhabiting both riparian and upslope areas (80% conifer per stand inventory documented Belt (1997)). The catchment was treated with a mid-rotation pre-commercial thinning in 1981 and a commercial thin in 1997, and fertilized in 1998 with 224 $kg\,N\,ha^{-1}$ as urea (Stednick and Kern, 1992). Substrate in the mainstem channel of NBLG is primarily gravels (45.0% ± 0.10 SD) and fines (< 1 mm; 28.9% ± 0.08 SD) with occasional cobbles, boulders, and bedrock (unpublished data).

The upper portion of NBLG was clearcut harvested (35 ha) in summer 2009 using contemporary harvesting practices and BMPs. In

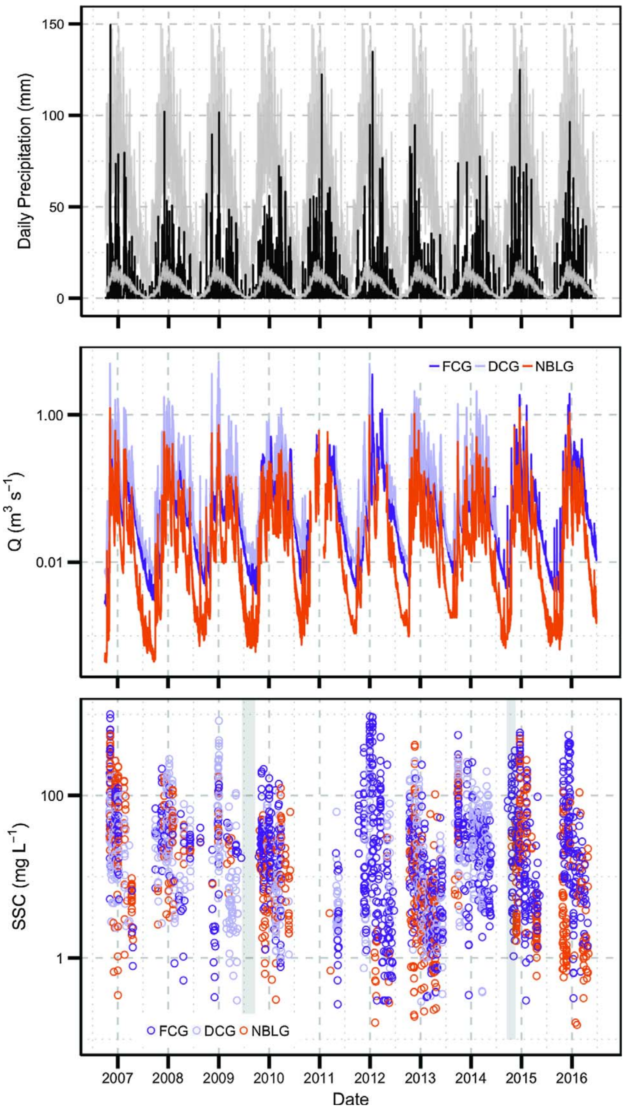

Fig. 2. (Upper panel) Daily precipitation (black) from composite of 4 gages at the Alsea Watershed Study. Gray lines are the mean (lower) and max daily precipitation from the Alsea Fish Hatchery Weather Station (1954–2017). (Middle panel) instantaneous discharge from the three major watersheds. (Lower panel) Suspended sediment concentrations from the three major watersheds. The vertical gray bars correspond to the Phase I and Phase II harvests.

Table 1
Site summary.

Station	Area [ha]	Mean elevation [m – NAVD88]	Elevation range [m]	Mean watershed gradient [degrees]	Mean channel gradient[a] [m m^{-1}]
FCG	219	280	263	28	0.025
NBLG	94	220	239	37	0.014
DCG	315	311	326	43	0.018

[a] Moring and Lantz, 1975.

fall of 2014, most of the lower NBLG watershed was harvested employing the same standards. A final 2.4 ha patch of timber in the lowermost portion of the drainage was harvested in July 2015. In both entries, ground-based equipment was used where topography allowed, while cable-based equipment was used on steeper slopes. In non-fish-bearing reaches, there was no requirement for overstory retention so stream-adjacent trees were harvested. On the fish-bearing portion of the stream, a ~15 m wide RMA was retained on each side of the stream in accordance with the Oregon Forest Practices Act and Rules (ODF, 1994). Limited harvesting was allowed in RMAs according to tree and basal area retention requirements and further restrictions on near-stream disturbance from roads, yarding, and site-preparation. These rules have recently undergone changes that can increase the width and restriction of management activities within the RMA. NBLG was replanted within 2 years after harvest.

Deer Creek is a 2nd-order stream with a mean watershed elevation of 311 m, a mean watershed gradient of 43°, and a mean channel gradient of 0.018 m m^{-1} (Table 1). Current canopy vegetation consists of Douglas-fir stands of various age-classes. Red alder is present in the riparian areas and on some hillsides and, as of 1992, represented only 36% of the forest composition (Belt, 1997). The original Alsea Watershed Study treatment for Deer Creek consisted of three small patch-cuts with retention of vegetated stream buffers. Additional (post-AWS) timber harvesting includes three small patch-cuts and commercial thinning in two of the three original patch-cuts. Silvicultural activity since the original study is considered to be relatively minor and inconsequential to sediment yield; therefore, the watershed is used here as a secondary control.

The original Alsea Watershed Study helped usher in practical management tools intended to reduce sediment inputs to surface waters from timber harvesting, but it was also a cautionary tale about measuring land use effects against natural variability (Beschta and Jackson, 2008). Even before treatments these watersheds displayed large variability of annual sediment yields. Flynn Creek averaged over twice the annual sediment yield during the seven-year pre-treatment period as NBLG. Within streams, annual variability was even greater. During the pre-treatment period FCG had a high annual sediment yield that was nearly 20-times greater than the lowest annual sediment yield (Beschta and Jackson, 2008) .

Needle Branch (NBLG), which had 86% of the watershed harvested, a "hot" (severe) slash broadcast burn, and no protection of the riparian area, showed a significant increase in suspended sediment yields compared to the expected levels (using the pretreatment relationship with the control, FCG). This response was especially dramatic the first years after timber harvesting and site preparation (1967, 271 Mg km^{-2} increase over background). The average annual sediment yield increase during the post-treatment period was estimated by Harris (1977) to be 181% (114 Mg km^{-2}), a significant increase ($p < .05$) in SSC following unrestricted timber harvesting. Sediment yields approached pre-treatment range by the end of the study (Harris, 1977; Moring, 1975a,b). Deer Creek, with 25% of the watershed harvested in 3 patch cuts, less severe broadcast burns in 2 units, and vegetation buffers along stream reaches, experienced a lesser and more variable response. In 1965, before completion of the harvesting and site-preparation but after road construction, a major storm increased sediment yield in all three watersheds, but especially DCG, due to a road failure. Again, in 1972, a major storm caused high sediment yields in DCG with a much subtler response in NBLG. Average sediment increases over the post-treatment period for DCG were estimated by Harris (1977) to be 25% (26 Mg km^{-2}), which was not statistically significant.

While the water quality response in NBLG is often the focus of discussion, DCG provided equally important lessons. The DCG riparian buffers minimized sediment yields from the channels, but road failures contributed large sediment pulses during major storms (see Fig. 18 in Moring (1975b). Buffers or other riparian protection measures can minimize sediment losses but other practices in the watershed also need to be considered. Occasionally, poor road construction and maintenance or site-preparation practices (i.e., severe prescribed burn in NBLG) that alter the forest floor and soil (especially near channels), can overwhelm the benefits of riparian management.

2.2. Instrumentation and data collection

Suspended sediment concentrations (SSC), discharge (*Q*), and daily precipitation were collected in all three of the study watersheds from October 2005 (WY2006) to June 2016 (WY2016). Discharge and suspended sediment were measured at compound broad-crested concrete weirs located at the watershed outlets of Flynn Creek (FCG), Needle Branch (NBLG), and Deer Creek (DCG). Precipitation was measured in tipping buckets (Davis Rain Gages, Texas Electronics, or Onset depending on availability with Onset event loggers) at four locations near the outlets of each watershed (Fig. 1). We averaged precipitation across all three watersheds because of gaps in the record and the close proximity of the gages.

Water samples for suspended sediment analysis were collected in auto samplers (ISCO 3700, Teledyne ISCO, Inc., Lincoln, NE). The auto samplers were triggered based on both a turbidity and minimum stage threshold (Lewis and Eads, 2009). Turbidity was measured using OBS-3-L turbidity sensors (D & A Instrument Co., Port Townsend, WA), which use an optical backscatter method to measure turbidity in the range of 0–4000 Formazin Turbidity Units (FTU). All stage and turbidity data were recorded with a CR-10(X) datalogger at 10 min intervals (Campbell Scientific, Inc., Logan, UT).

Over the 11 water years of this study a total of 4405 water samples were collected with automatic samplers, including total annual samples of 89–355 at FCG, 0–327 at DCG, and 2–226 at NBLG (Table 2). The majority of samples were collected during relatively high flow conditions above 0.2 $m^3 s^{-1}$ for FCG and DCG and above 0.07 $m^3 s^{-1}$ for NBLG. These thresholds correspond to unit discharges between 0.02 and 0.03 mm s^{-1}.

All water samples were analyzed for suspended sediment concentration at the Oregon State University Department of Forest Engineering, Resources & Management Forest Hydrology Lab. The samples were vacuum filtered using a 1.5 µm glass fiber filter paper (Whatman 934-AH), dried at 105 °C, and weighed following standard protocols.

Stage was recorded every 10 min between 2005 and 2016 with a CS420-L Druck pressure transducer (Druck Inc., New Fairfield, CT). We developed rating curves for each watershed from 40–59 manual measurements of stage and discharge primarily collected between 2006 and 2016 (3–6 pairs per year). The stage-discharge relationships were best described by a 3rd order polynomial for FCG, 2nd order polynomial for NBLG, and a power relation for DCG.

Uncertainty in the rating curve was assessed by conducting 1×10^6 Monte Carlo simulations randomly varying the parameters of the rating curve fits. The uncertainty in the stage data varied between 4 and 8% among the 3 sites and was assessed by comparing the electronic and reference stage values collected over a wide range of flows. The overall uncertainty in the 10-min discharge data, combining both sources of error, varied between 11–18% for FCG, 11–23% for NBLG, and 10–18% for DCG.

Except for WY2016, most years had almost complete coverage (> 95%) of *Q* data (Table 3). Personnel and technical difficulties resulted in partial years of data in water years 2011 and 2012 across all watersheds. Unfortunately, the year with the highest mean annual precipitation was 2011, which was two years after the Phase I harvest (Table 4). This year had the lowest *Q* data coverage for all sites and was also the lowest *Q* data coverage year for FCG and DCG (WY2014 had lowest SSC coverage for NBLG). These missing data result in modifications to the specific analyses that could be conducted throughout the study—in particular, sediment load and yield calculations.

Table 2
Summary of suspended sediment concentrations (mg L^{-1}). Treat. = treatment, NA = data not available.

WY	Treat.	FCG			DCG			NBLG		
		Mean	Max	N	Mean	Max	N	Mean	Max	N
2006	Pre	47.8	446	172	32.8	379	121	43.2	235	61
2007		130.1	1632	160	127.7	1493	165	79.6	667	129
2008		48.2	1166	163	53.8	735	136	32.3	198	94
2009	Phase I	78.2	1249	89	65.1	1136	147	41.9	170	23
2010		39.9	288	171	578.2	6410	117	22.1	156	117
2011		7.6	28	55	6.3	63	29	1.7	4	18
2012		142.0	2002	355	43.1	498	141	2.1	30	47
2013		32.2	554	287	29.1	294	327	28.7	419	226
2014	Phase II	72.9	3557	151	41.5	260	125	7.3	10	2
2015		65.5	592	176	NA	NA	NA	51.4	502	113
2016		68.2	553	137	NA	NA	NA	11.4	112	102

2.3. Comparison of SSC among sites

To compare suspended sediment concentration, we used step-wise multiple linear regression to develop a model to predict suspended sediment concentration (SSC) from a model of watershed (WS), phase of the treatment (P), hydrographic limb (L), and unit area discharge (Unit *Q*). Covariates were used to improve model prediction. These included cumulative *Q* within WY (C), day of WY (D), daily precipitation (DP), and the previous day's precipitation (PP). The prediction of SSC was made with the following equation:

$$\begin{aligned} SSC = {} & \beta0 + \beta1(C) + \beta2(D) + \beta3(DP) + \beta4(PP) + \beta5(DP) + \beta6(WS) \\ & + \beta7(P) + \beta8(L) + \beta9(\text{Unit Q}) + \beta10(WS*P) + \beta11(WS*L) \\ & + \beta12(WS*\text{Unit Q}) + \beta13(P*L) + \beta14(P*\text{Unit Q}) \\ & + \beta\beta15(L*\text{Unit Q}) + \beta16(WS*P*L) + \beta17(WS*P*\text{Unit Q}) \\ & + \beta18(WS*L*\text{Unit Q}) + \beta19(P*L*\text{Unit Q}) \\ & + \beta20(WS*P*L*\text{Unit Q}) \end{aligned} \quad (1)$$

where the β terms are the coefficient for each variable or combination of variables. We used unit area *Q* (mm s^{-1}) for all analyses involving *Q* due to the differences in watershed area. We log-transformed SSC, unit area *Q*, and precipitation to improve normality in the data distributions. Model selection was conducted using Akaike Information Criterion (AIC) (Akaike, 1974). Variance inflation factors were used to examine the multi-collinearity of each variable in the model. If the square-root of the variance inflation factor was greater than two, the variable was removed. This analysis was conducted using the 'car' and 'MASS' packages within R (Venables and Ripley, 2002; Fox and Weisberg, 2011; R Core Team, 2016).

Log-log relationships of *Q* and SSC result in biased estimates predicted SSC. We examined the relationship between the predicted (independent) and observed (dependent) values for SSC, and applied a correction factor to the predicted values. We multiplied all predicted values by the slope ($m = 1.983$) produced by the linear model of the untransformed observed versus predicted SSC data. The resulting relationship of observed versus corrected-predicted SSC resulted in a slope of 1.0 (determined to be unbiased). Corrected-predictions of instantaneous SSC were then multiplied by the time-period (i.e., 10 min) and the discharge for that period to calculate instantaneous suspended sediment loads. These values were summed by watershed over the entire year to determine the annual loads. Annual loads were divided by watershed area to determine annual suspended sediment yields.

We analyzed the differences in SSC among downstream sites and across harvest entries with an analysis of covariance (ANCOVA) using the model developed from the multiple linear regression procedure. Watershed (FCG, DCG, and NBLG) and phase (pre-harvest, post-Phase I-harvest, and post-Phase II-harvest) were used to examine differences in SSC among watersheds and time-periods. To determine if the treatment effect expanded or contracted differences between FCG and NBLG we performed a contrast of contrasts. We compared all periods' differences between FCG and NBLG, which resulted in three contrasts of contrasts (Pre-Phase I, Pre-Phase II, and Phase I–Phase II). An α value of 0.05 was

Table 3
Summary of discharge ($m^3 s^{-1}$) data. Data coverage represents the proportion of the year with discharge data. Treat. = treatment, NA = data not available.

WY	Treat.	FCG			DCG			NBLG		
		Mean	Max	Data coverage	Mean	Max	Data coverage	Mean	Max	Data coverage
2006	Pre	0.13	1.37	0.75	0.21	2.45	0.59	0.05	0.49	0.75
2007		0.10	1.69	1.00	0.19	4.98	1.00	0.04	1.23	1.00
2008		0.09	0.78	1.00	0.18	1.75	1.00	0.04	0.59	1.00
2009	Phase I	0.09	1.32	1.00	0.19	5.32	0.84	0.03	0.73	1.00
2010		0.12	0.64	0.93	0.16	1.23	0.75	0.05	0.33	1.00
2011		0.07	0.56	0.57	0.05	0.38	0.42	0.04	0.61	0.72
2012		0.13	3.54	0.93	0.11	4.93	0.62	0.02	0.98	0.66
2013		0.12	1.20	0.99	0.20	2.11	1.00	0.05	1.03	1.00
2014	Phase II	0.10	0.95	0.99	0.20	2.11	0.77	0.04	0.50	0.99
2015		0.10	1.86	1.00	NA	NA	NA	0.04	1.26	1.00
2016		0.14	1.92	0.84	NA	NA	NA	0.06	1.07	0.84

Table 4
Summary of annual precipitation (mm) for the entire Alsea Watershed Study. Data coverage represents the proportion of the year with precipitation data. Treat. = treatment.

WY	Treat.	Annual	Data coverage
2006	Pre	2603	1.00
2007		2495	1.00
2008		2360	1.00
2009	Phase I	2028	1.00
2010		2396	1.00
2011		2621	1.00
2012		2488	1.00
2013		2539	1.00
2014	Phase II	1932	1.00
2015		2056	1.00
2016		2106	0.84

used to determine statistical significance. Post-hoc analyses of means and contrasts between phases and watersheds was conducted using the least-squares means procedure from the R package 'lsmeans' (Lenth, 2016). The least-squares means procedure accounts for all variables, including covariates, when performing post-hoc tests and calculating means and variances from the data-set. To reduce the chance of a type I error (i.e., false-positive) we used the Bonferroni correction during all contrasts and least-squares means estimates.

3. Results

3.1. Effects of contemporary harvesting on suspended sediment

As expected, there was a positive power relationship between unit area *Q* and SSC within each watershed (Fig. 3). The stepwise multiple linear regression procedure provided strong evidence ($p < .001$) that all covariates (hydrograph limb, cumulative *Q* within WY, day of WY, daily precipitation, previous day's precipitation) were related to SSC across all watersheds (Table 5). The variance inflation factor of day of WY indicated that it was collinear with other factors so was dropped from the model. The full model that predicted SSC had an r^2 of 0.583 and $p < .001$ (Fig. 4). This model was used in an ANCOVA procedure to test hypotheses that contemporary harvesting practices affect the SSC and to determine SSC.

We found that there was no effect of contemporary forest harvesting practices on SSC. Both the mean and maximum SSC were greater in the reference catchments (FCG and DCG) compared to the harvested catchment (NBLG) across all WYs (Table 2). Moreover, in NBLG the mean SSC was 32 $mg\,L^{-1}$ (~63%) lower after the Phase I harvest and 28.3 $mg\,L^{-1}$ (~55%) lower after the Phase II harvest when compared to the pre-harvest concentrations. Compared to the reference watersheds, the mean SSC was 1.5-times greater in FCG (reference) compared

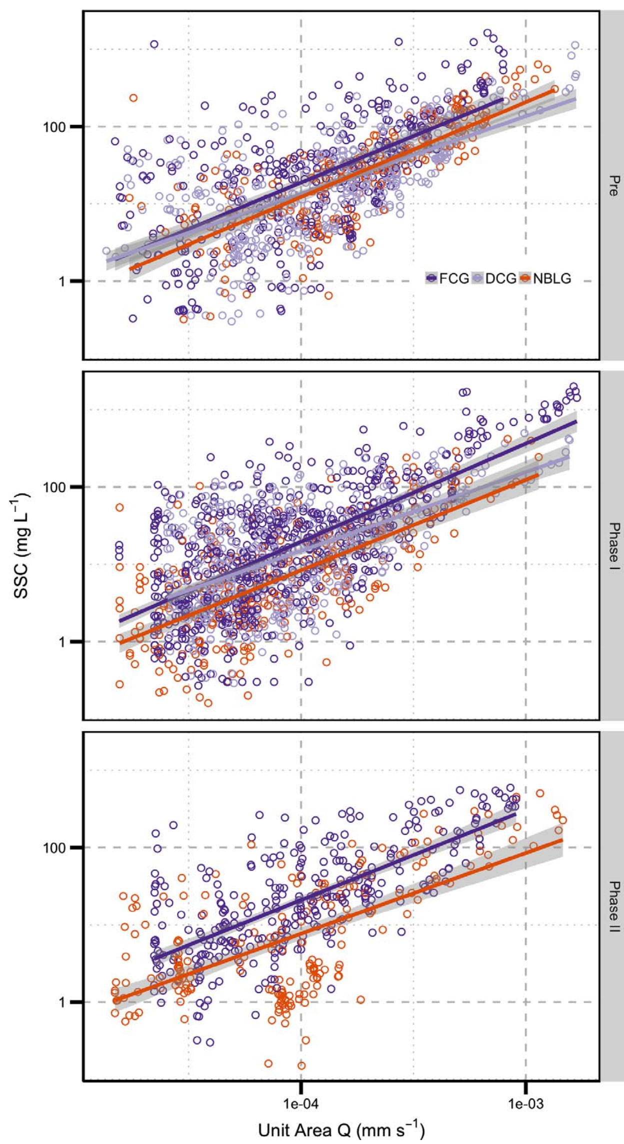

Fig. 3. Relationship between discharge and SSC Pre-harvest (2006–2009), Phase I harvest of the upper part of the Needle Branch watershed (2010–2013), and Phase II harvest of the lower part of the Needle Branch watershed (2013–2016). Lines indicate a simple linear regression of the unit area *Q* and SSC data. This regression was not used for analysis or flux calculation because other variables were found to be strong co-variates with SSC and thus a multiple regression model yielded more robust estimates.

Table 5
Coefficients of linear model of SSC. Fill model a had an r^2 of 0.5831 and a p-value < .001. NA = coefficient not able to be calculated.

Variable	Coefficient	SE	p-value
Intercept	22.2661	2.4609	.0000
ln(Unit Q)	0.8418	0.1078	.0000
DC315	−0.5594	3.7005	.8800
NB86	5.0988	4.0964	.2130
Phase (Phase I)	−0.3443	3.1644	.9130
Phase (Phase II)	0.4902	3.6959	.8940
Limb (Falling)	0.9217	2.9682	.7560
Proportion Cumulative Q	−0.5648	0.0683	.0000
ln(Precipitation)	0.0982	0.0178	.0000
ln(Precipitation lagged 1 day)	0.2078	0.0194	.0000
ln(Unit Q):WSDC315	−0.0145	0.1619	.9290
ln(Unit Q):WSNB86	0.2592	0.1811	.1520
ln(Unit Q):Phase I	−0.0194	0.1386	.8890
ln(Unit Q):Phase II	0.0204	0.1626	.9000
DC315:Phase I	−1.3790	5.2166	.7920
NB86:Phase I	−6.2116	6.2193	.3180
DC315:Phase II	NA	NA	NA
NB86:Phase II	−5.3078	5.7899	.3590
ln(Unit Q):Falling	0.0697	0.1301	.5920
DC315:Falling	−0.2712	4.3014	.9500
NB86:Falling	−3.0770	4.8998	.5300
Phase I:Falling	0.7324	3.7775	.8460
Phase II:Falling	−3.4036	4.4282	.4420
ln(Unit Q):DC315:Phase I	−0.0685	0.2279	.7640
ln(Unit Q):NB86:Phase I	−0.2778	0.2721	.3070
ln(Unit Q):DC315:Phase II	NA	NA	NA
ln(Unit Q):NB86:Phase II	−0.2364	0.2548	.3540
ln(Unit Q):WSDC315:Falling	−0.0097	0.1882	.9590
ln(Unit Q):WSNB86:Falling	−0.1531	0.2167	.4800
ln(Unit Q):Phase I:Falling	0.0256	0.1650	.8770
ln(Unit Q):Phase II:Falling	−0.1564	0.1940	.4200
DC315:Phase I:Falling	−5.2348	5.9828	.3820
NB86:Phase I:Falling	0.2905	7.1184	.9670
DC315:Phase II:Falling	NA	NA	NA
NB86:Phase II:Falling	−0.8209	6.9029	.9050
ln(Unit Q):DC315:Phase I:Falling	−0.2217	0.2611	.3960
ln(Unit Q):NB86:Phase I:Falling	0.0411	0.3115	.8950
ln(Unit Q):DC315:Phase II:Falling	NA	NA	NA
ln(Unit Q):NB86:Phase II:Falling	−0.0083	0.3032	.9780

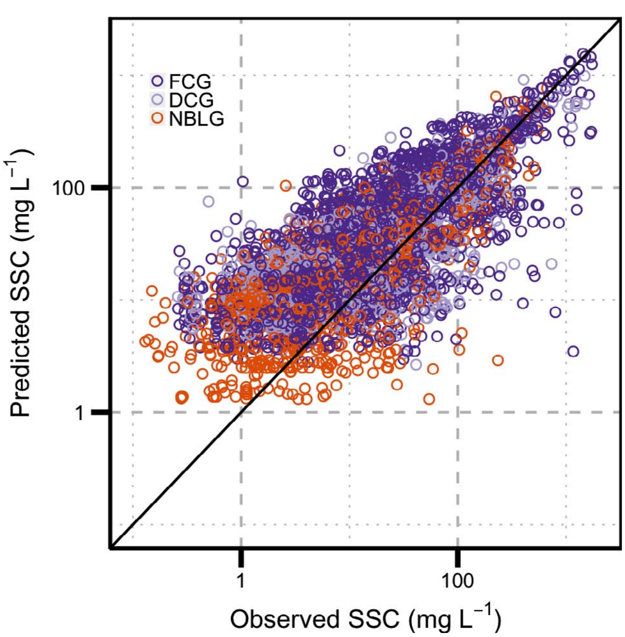

Fig. 4. Observed versus predicted SSC. Model coefficients are reported in Table 5. The full linear model had an r^2 of 0.5831 and a p-value < .001.

Table 6
Summary of the analysis of covariance of SSC between FCG, DCG, and NBLG.

Factor	p-value
ln(Unit Q)	.0000
WS	.0000
Phase	.6410
Limb	.0000
Cumulative WY Q	.0000
ln(Daily Precipitation)	.0000
ln(Previous Day's Precipitation)	.0000
ln(Unit Q)*WS	.0128
ln(Unit Q)*Phase	.0067
WS*Phase	.0176
ln(Unit Q)*Limb	.9717
WS*Limb	.3440
Phase*Limb	.8104
ln(Unit Q)*WS*Phase	.0811
ln(Unit Q)*WS*LIMB	.5995
ln(Unit Q)*Phase*LIMB	.2479
WS*Phase*Limb	.1194
ln(Unit Q)*WS*Phase*Limb	.8210

to NBLG during the pre-harvest period. After the Phase I harvest the mean SSC in FCG was 3.1-times greater and after the Phase II harvest was 2.9-times greater when compared to the SSC in NBLG, the harvested watershed. We observed a similar trend when comparing the SSC between NBLG and the other reference watershed, DCG (Table 2) for each watershed and phase (highest order significant interaction). Using this model to perform an ANCOVA, indicated that phase and watershed significantly interacted suggesting that the between watershed SSC relationships were unique to each treatment phase (Table 6).

The harvested watershed (NBLG) had significantly lower SSC than both FCG and DCG for all treatment phases (Fig. 5). The significant interaction (Table 6) between phase and watershed was driven by the dynamics of FCG and DCG in relation to one another, and does not appear to be the result of a treatment effect. We found that none of the contrasts between watersheds examining the magnitude of change between pre- and post-treatment (i.e. a contrast of contrasts) were statistically significant ($p > .97$), which determined if a treatment effect expanded or contracted differences between the treated and reference watersheds. This suggests that harvesting in the upper or lower portion of NBLG had no effect on SSC during any period and that any changes in SSC were driven by differences among the WY that were not explained by the covariates (time, *Q*, and precipitation).

Our analysis by Phase would have treated each WY within that period the same. This decision protected our analysis from some periods with missing data, but could have missed SSC dynamics active in shorter time frames. We performed the least-mean squares and contrasts procedure again using WY instead of phase as the period of time (Bonferroni adjusted $\alpha = 0.05$). The differences in least-square means of SSC between FCG and NBLG across all years was 1.93 mg L^{-1}. The least square mean SSC from FCG was significantly larger than NBLG during the pre-treatment WYs, by 2.24–3.97 mg L^{-1} ($p < .0001$). The post-harvest least square mean from FCG was significantly larger than NBLG during 2010, 2012, 2013, 2015, and 2016, by 1.65–4.06 mg L^{-1}. The two watersheds were not different during WY 2011; however, SSC from FCG was still 5.05 mg L^{-1} larger than NBLG. So while we may have missed data from a critical period in 2011 and 2012, SSC from FCG was always higher than NBLG and therefore there was no apparent evidence in our data-set that indicates a higher SSC as a result of harvesting.

3.2. Suspended sediment yields

The linear model developed and presented in Table 5 was used to calculate the suspended sediment yields from all three watersheds. The results for NBLG and FCG are presented in Fig. 6. We restricted the

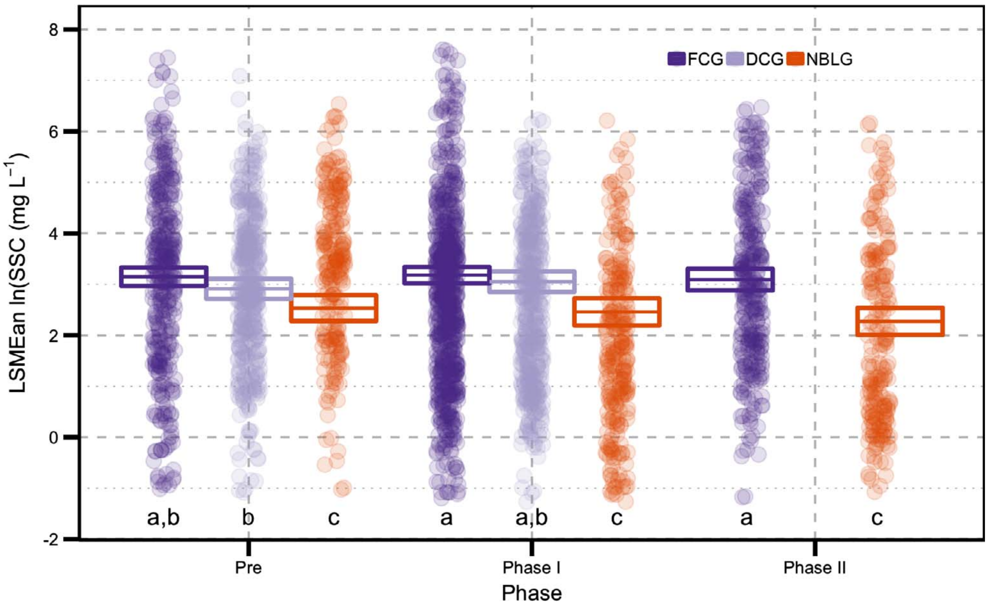

Fig. 5. Natural log transformed SSC (points) with least-squared means of natural log transformed means (boxes). Mid-line of box is the predicted least-square mean and upper and lower bounds of boxes are the 5th and 95th percentile. Least square means' confidence intervals and pairwise contrasts have been corrected for multiple comparisons using Bonferroni's adjustment. Letters indicate homogenous subsets as determined by pairwise contrasts.

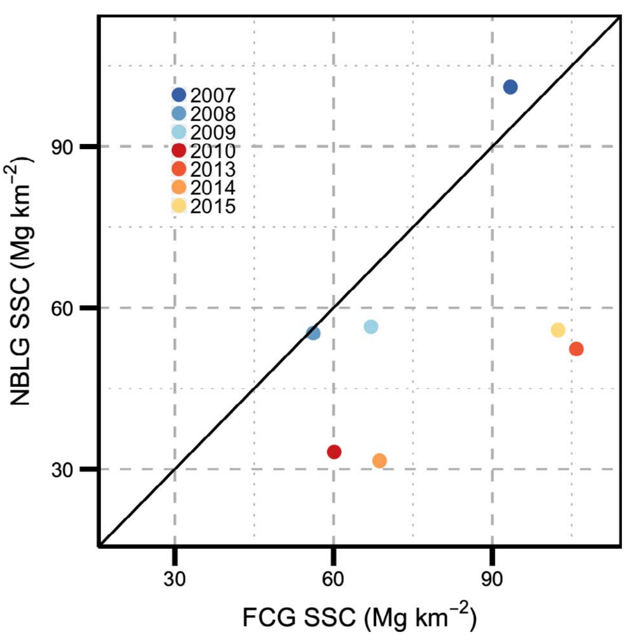

Fig. 6. Suspended sediment yield of treated and reference watersheds. 2007–2009 were Pre-treatment years, 2010 and 2013 were post-Phase I treatment, and 2014 and 2015 were post-Phase II treatment. Only years in which 80% of the discharge data were available were considered.

analysis to years with at least 80% discharge data coverage; therefore, 2, 3, and 5 years were omitted for FCG, NBLG, and DCG (NAs in Table 7). The timing of missing data of the years included in the analysis could be important for suspended sediment yields—we found that 0–2, 0–5, and 0–59 days per year were missing between October and March of each WY for FCG, NBLG, and DCG, respectively. Therefore, our sediment load calculations are fairly robust for FCG and NBLG, but maybe weaker for DCG, especially 2009 and 2010 which had the most missing days (46 and 59 days, respectively, each year). The calculated yields varied between 31 and 313 Mg $km^{-2} yr^{-1}$ (Table 7). The highest rates were calculated for FCG during 2012, which corresponded to the year with the highest annual precipitation (Table 4). Pre-treatment sediment yields (2007–2009) were about equal between the two watersheds (70.6 and 70.8 Mg $km^2 yr^{-1}$ for FCG and NBLG, respectively). During the post-treatment (both Phases), the suspended sediment yield of NBLG decreased relative to FCG, which was not reflected in the analysis of SSC.

4. Discussion

4.1. Summary and comparison to other studies of contemporary harvesting practices

Our findings indicated that clearcut harvesting, using contemporary harvesting techniques and BMPs (i.e., stream buffers, smaller harvest units, no broadcast burning, leaving material in stream channels), had little effect on suspended sediment in the Oregon Coast Range. This suggests that retention of a riparian buffer and less intensive site preparation practices (broadcast burning was not conducted) may be effective at preventing additional sediment delivery to streams and reducing potential impacts to water quality and aquatic habitat across this region. Similar catchment-scale studies assessing the effectiveness of contemporary forest harvesting practices at limiting suspended sediment concentrations and yields have illustrated mixed results (Binkley and Brown, 1993; Gomi et al., 2005). For example, suspended sediment has been shown to increase (Macdonald et al., 2003), decrease (Grant and Wolff, 1991; Choi et al., 2014), and not change (Hotta et al., 2007) following contemporary forest harvesting.

Our study isolated the effects of upland forest harvesting activity on sediment production as no new roads were constructed within the Needle Branch watershed. Most studies that have addressed contemporary practices including roads built within the experimental watersheds, have reported increases in suspended sediment load (Arthur et al., 1998; Wear et al., 2013). A survey of nearly 200 timber harvest units in the Sierra Nevada and Cascade Mountains of California indicated that forest harvesting alone rarely produces substantial erosion and sedimentation (Litschert and MacDonald, 2009). Rather, linear features such as roads and skid trails, as well as stream crossings, are typically the principal source of sediment (Luce and Black, 1999; Motha et al., 2003; Sheridan and Noske, 2007). There have been other observations of no changes in suspended sediment after road building in the Oregon Coast Range (Arismendi et al., 2017) and harvesting with BMPs with new roads and linear features (Wynn et al., 2000; Studinski et al., 2012). However, the variability in suspended sediment response to contemporary forest practices may depend on catchment physiography and lithology, as illustrated in a recent multi-catchment analysis in the Oregon Coast Range (Bywater-Reyes et al., 2017).

Table 7
Flux and yield of suspended sediment from each watershed for the contemporary study (this study) and historical study. Letters in summary panel indicate homogenous subsets. Treat. = treatment, NA = data not available, Phase II = Phase II, Contemp. = Contemporary.

WY	Treat.	FCG		NBLG		DCG	
		[Mg yr^{-1}]	[Mg km^{-2} yr^{-1}]	[Mg yr^{-1}]	[Mg km^{-2} yr^{-1}]	[Mg yr^{-1}]	[Mg km^{-2} yr^{-1}]
Contemporary							
2007	Pre	193	92	88	102	401	127
2008		116	55	46	53	218	69
2009		135	64	49	57	402	127
2010	Phase I	127	60	28	33	NA	NA
2011		NA	NA	NA	NA	NA	NA
2012		658	313	NA	NA	NA	NA
2013		227	108	44	51	291	92
2014	Phase II	147	70	27	31	NA	NA
2015		214	102	44	52	NA	NA
Historical[a]							
1959	Pre	62	30	15	17	97	31
1960		46	22	10	12	97	31
1961		239	114	46	54	361	115
1962		96	46	35	41	125	40
1963		81	38	29	34	172	55
1964		160	76	46	53	226	72
1965		899	428	107	124	1136	361
1966		206	98	92	106	316	100
1967	Post	93	44	225	262	792	251
1968		47	23	122	142	231	73
1969		100	48	128	149	92	29
1970		86	41	58	67	171	54
1971		134	64	103	120	156	50
1972		780	372	129	150	1498	475
1973		41	20	33	38	139	44
Summary							
Contemp.-Pre		148	71	61	71	340	108
Contemp.-Post		275	131	36	42	291	92
Historical-Pre		224	106	47	55	316	100
Historical-Post		183	87	114	133	440	140

[a] Historical data from Stednick (2008) and yields have been adjusted for differences in watershed area calculated historically and here (WS = old area (km^2)/new area (km^2)): FCG = 2.02/2.10, NBLG = 0.71/0.86, and DCG = 3.03/3.15.

4.2. Comparison of results to original AWS

Our study provided a unique opportunity and enabled a robust assessment of whether contemporary harvesting practices reduced suspended sediment yields compared to historical (1960s) practices. Current and historical data from the same watersheds suggest that contemporary practices are more effective at mitigating sedimentation than historical practices. For example, the original Alsea Watershed Study showed that historical practices, including clearcutting without riparian buffers, road building, and slash burning resulted in ~2.8 times increases in annual sediment yields (Brown and Krygier, 1971; Beschta, 1978) and aquatic ecosystem degradation (Hall, 2008). Moreover, sediment increases in the post-harvest period were 253% greater in Needle Branch and 117% greater in Deer Creek, relative to the pre-harvest periods (Beschta and Jackson, 2008). Comparatively, the current study illustrated that annual sediment yields in Needle Branch were lower than in Flynn Creek (reference catchment) after contemporary forest harvesting. Flynn Creek had the highest sediment yield of the contemporary period in 2012, whereas there was too much missing data in 2012 to calculate suspended sediment yields for NBG and DCG. Lower sediment yields in Needle Branch that followed treatment could be the result of a reduction in supply caused storms during 2012 which had the highest annual precipitation. However, lower suspended sediment yields from Needle Branch after contemporary harvesting appear to be within the range of variability, with no effects from forest harvesting.

Statistically, we performed a simple ANCOVA procedure to compare suspended sediment yields from NBLG pre- and post-treatment for the historical and contemporary periods with suspended sediment yields from FCG and DCG as covariates. We found there was strong evidence for a difference between the periods ($p < .001$ for FCG and $p = .005$ for DCG). Post-hoc comparisons revealed only the historical post-treatment period was significantly different from the rest of the periods. The suspended sediment yield from NBLG had returned to yields similar to the pre-harvest period from the historical harvesting activity and that contemporary harvesting did not affect that status. Calculations of suspended sediment export from the original Alsea Watershed Study were conducted by multiplying Q weighted SSC by daily Q, which would have resulted in a lower estimation of suspended sediment than we calculated for the contemporary period due to the non-linear nature of the Q-SSC relationship. If suspended sediment export was measured and calculated using the same methods, estimates of the impacts of historical practices on suspended sediment likely would have been greater than shown here. Interestingly, plots of the contemporary suspended sediment yields together with the historical yields showed that the pre-treatment yields were similar between the watersheds during each of the time periods (Fig. 7 and Table 7). This provides evidence that the harvested watersheds had recovered and there was no legacy effect from the historical forest harvesting activity.

Other retrospective paired watershed studies have shown that contemporary harvesting practices can greatly reduce water quality impacts, including SSC and sediment yields. Fraser et al. (2012) reported on a return to the Grant Forest in Georgia, which was first harvested and monitored in the 1970s. In the original study, both SSC and sediment yields increased and the authors identified specific management activities contributing to those increases. In the subsequent study, Fraser et al. (2012) found in that wider buffers, better roads, and other improved BMPs resulted in no change to the SSC;

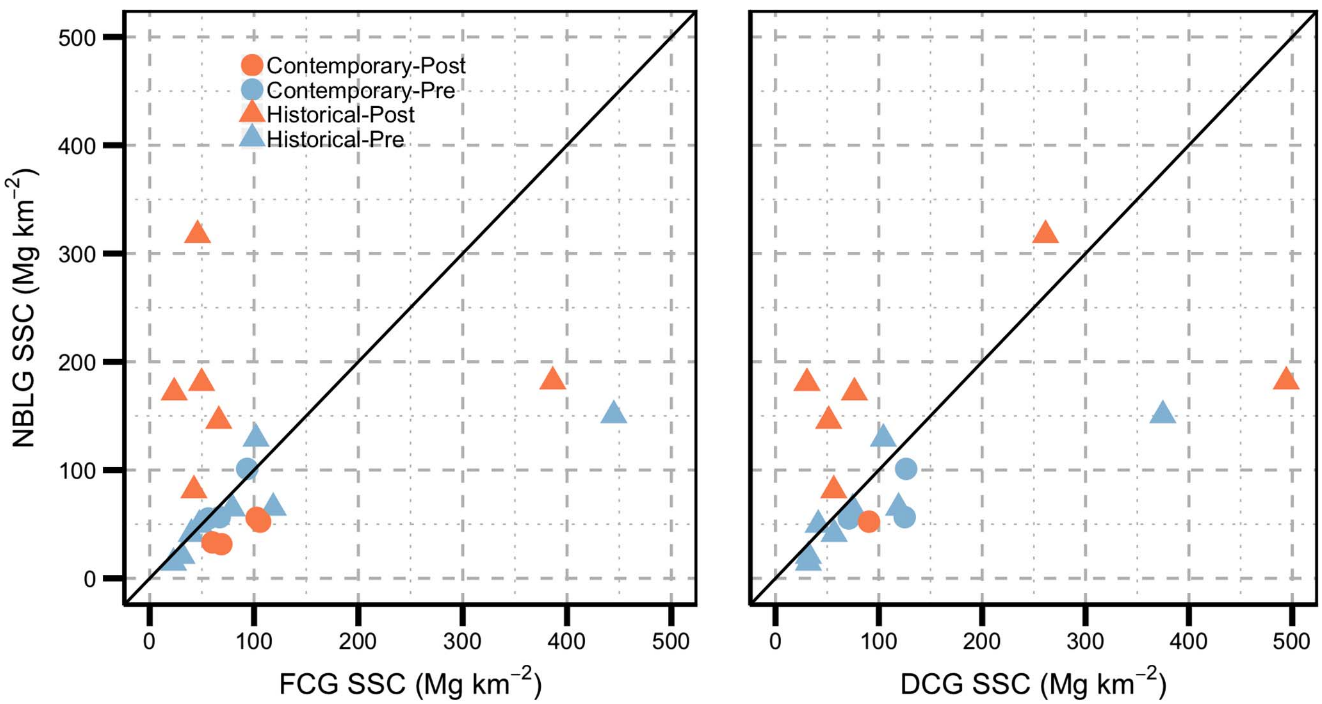

Fig. 7. Suspended sediment yield of treated and reference watersheds from this study (contemporary-pre and –post) and the Original Alsea Watershed Study (historical-pre and –post). Historical data from Stednick (2008) and yields have been adjusted for differences in watershed area calculated historically and here (WS = old area (km^2)/new area (km^2)): FCG = 2.02/2.10, NBLG = 0.71/0.86, and DCG = 3.03/3.15.

however, sediment yields did increase due to increased discharge following harvesting. Another retrospective study near Alto, Texas compared a harvest with BMPs in 2002 with the response to a harvest in 1981 using shearing and windrowing site-preparation. McBroom et al. (2008) reported that the greatest first-year increase in sediment yields following the 2002 harvest among the small watersheds studied was about one-fifth of that observed after the 1981 harvest. Other studies, such as Caspar Creek (California), are scheduled to be harvested over the next couple of years and monitored for discharge and SSC. These data will eventually contribute additional knowledge comparing historical and contemporary harvesting practices on suspended sediment dynamics. In general, these studies have found that contemporary BMPs have decreased suspended sediment concentrations relative to historical practices.

Finally, evidence from other lines of inquiry are emerging that demonstrate contemporary harvesting practices in the region have reduced sediment export from managed watersheds. A study of lake sedimentation using sediment cores found reduced sedimentation rates associated with improved BMPs, which were instituted in the 1970s in Loon Lake, an Oregon Coast Range lake, with a watershed underlain by the same sandstone geologic formation as the Alsea Watershed Study (Richardson, 2017; Richardson et al., submitted for publication). These studies from the sandstone dominated portions of the Oregon Coast Range support the assertion that contemporary forest harvesting practices, have reduced sediment concentrations and export from the historical high rates of sedimentation found during periods of unrestricted harvesting.

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