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Did changes in western federal land management policies improve salmonid habitat in streams on public lands within the Interior Columbia River Basin?

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Abstract Historic management actions authorized or allowed by federal land management agencies have had a profound negative effect on salmon, trout, and char populations and their habitats. To rectify past failings, in the 1990s, federal agencies in the Interior Columbia River Basin modified how they conducted land management activities to foster the conservation of aquatic species. The primary policy changes were to provide additional protection and restoration of lands near streams, lakes, and wetlands. What remains uncertain was whether these changes have altered the trajectory of stream habitat conditions. To address this question, we evaluate the status and trends of ten stream habitat attributes; wood frequency, wood volume, residual pool depth, percent pool, pool frequency, pool tail fines (< 6 mm), median particle size, percent undercut banks, bank angle, and streambank stability in managed and reference catchments following changes in management policies. Our review of these data support the hypothesis that changes made in management standards and guidelines in the 1990s are related to improved stream conditions. Determining the precise magnitude of changes in stream conditions that resulted from the modification of land management policies is difficult due to the shifting environmental baseline. By understanding and accounting for how changes in stream conditions reflect improved land management policies and broader environmental trends, federal agencies will be better situated to make project level decisions that benefit aquatic resources.

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Introduction

The relationship between the decline of the Pacific Northwest's native salmon, trout, and char (Oncorhynchus sp., Salvelinus confluentus) (Nehlsen et al. 1991) and historic land management actions (Meehan 1991) resulted in the Forest Service and Bureau of Land Management (BLM) dramatically altering how near stream management activities could be conducted in the region beginning in the mid-1990s (USDA/USDI 1994; USDA/USDI 1995; USDA 1995). In adjusting these policies, managers sought to reduce the threats land management posed to stream habitat conditions and give biologist more input into project designs. The goals, objectives, standards, and guidelines within these plans not only reduced management intensity near streams (passive restoration) but also invested millions of dollars to directly improve stream conditions (active restoration).

From the 1960s to the early 1990s, there were few limitations on actions federal land management agencies could undertake or permit near streams. During this

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time, protections provided to maintain stream conditions were insufficient to balance the risks posed by increasing timber harvest and a lengthening road system (Hicks et al. 1991; Dose and Roper 1994). This led to simplified stream channels with less instream wood, increased fine sediments on the streambed, and destabilized streambanks (Meehan 1991). This period followed decades (pre-1960s) where management actions such as the construction of valley bottom roads, channel straightening, and log drives had an even greater direct effect on stream channel conditions (Burnett et al. 2007; Steel et al. 2016).

One of the primary goals of amending planning documents (e.g., USDA/USDI 1994) in the 1990s was to increase the likelihood that new management practices would maintain the viability of native salmonids (Ratner et al. 1997; McHugh et al. 2017). The primary mechanism for improving stream conditions was to limit resource management such as timber harvest, road construction, livestock grazing, and other activities near streams (Boisjolie et al. 2017; Roper et al. 2018). Additional policy changes included guidelines to minimize sediment runoff from roads, requirements to conduct watershed scale analysis, the identification of a set of watersheds where greater protections of aquatic species were warranted, and to implement stream restoration projects.

Altering management strategies to increase the protection of salmonids and terrestrial species (e.g., northern spotted owls, *Strix occidentalis*) did not come without a cost. Concurrent with changes in management policies intended to improve stream condition was a 70% reduction in the amount of timber harvested from public lands in the region (Adams et al. 2006). The loss of timber harvesting opportunities negatively affected many rural communities (Charnley 2006; Thomas et al. 2006; Eichman et al. 2010). While the cost of sustainable forest management was high in some areas (Power 2006), plan modifications retained options for future forest management while trying to reverse negative trends in aquatic habitat. The social costs associated with less timber harvest make it imperative that federal land management agencies demonstrate these modifications are improving stream conditions.

While an increasing number of studies have established that changing land management practices near streams can improve conditions at intermediate spatial scales (Batchelor et al. 2015; Nusslé et al. 2017; Yeung et al. 2017), the ability to detect changes in stream conditions across a broad region has been more difficult (Larsen et al. 2004; Anlauf et al. 2011). An approach suggested to detect the effects of management changes at a large spatial scale is to compare the status and trend of stream conditions in watersheds subject to land management activities to those that are not (Kershner et al. 2004a; Stoddard et al. 2006; Hawkins et al. 2010). The notion behind such comparisons is that status and trends of streams in unmanaged areas—commonly referred to as reference areas—represent the expected status and trends of streams in managed areas. Differences found between conditions in managed and reference areas reflect the effects of past management actions and could track how changed land management policies have altered trajectories of managed stream conditions.

In evaluating the status and trend of stream habitat conditions across a large sample of reference and managed stream reaches, we envisioned several scenarios may reflect how stream conditions responded to the more protective public land management policies (Fig. 1; modeled after Samuelson and Rood 2011). The null model is that the state of stream attributes at large spatial scales was not historically affected by federal land management activities and the change in management policies had no measurable effect on the trend in stream conditions (H0). The second hypothesis is historic land management activities caused a divergence between managed and reference stream conditions and these differences have been maintained over time (H1). Results supporting H1 would suggest recent changes in management policies have been insufficient to detect improvement in salmonid habitat conditions. The third hypothesis represents what decision makers were likely expecting when they changed management direction in the 1990s; reference conditions would be stable following changes in policies, but managed stream conditions would converge towards reference conditions (H2a). However, it is also possible that if changes in management policies were insufficient, inappropriately targeted, or improperly implemented, that habitat conditions in managed streams could diverge from reference conditions (H2b).

We felt it important to incorporate the possibility that stream conditions in reference stream reaches may not be stable over decadal time frames either due to natural climatic cycles (Barlow et al. 2001; Andrews and Antweiler 2012), climate change (Kopf et al. 2015; Poff 2017), or other regionally concordant events (Larsen et al. 2004). A lack of stationarity could result in reference stream conditions trending over time (Hobbs et al. 2014). Our third hypothesis addresses two potential outcomes where trends in reference and managed stream reaches were of similar magnitude. After accounting for these trends, differences between managed and reference reaches could either be small and not detectable (H3a; similar to H0) or be large enough to detect (H3b; similar to H1). Our final two hypotheses also incorporate a lack stationarity, but under these scenarios, the trend in stream conditions in managed stream reaches are either converging to (H4) or diverging from (H5) reference conditions. Stream habitat conditions that trend in a manner that support H4 would generally be defined as management success. Stream habitat conditions that trend in a manner that support H5 could be defined as either a failure of management policies or the inability of the current management policies to overcome a historic deficit in stream conditions caused by past land management practices.

We evaluated which of the listed hypothesis (Fig. 1) best reflected the status and trends of ten stream habitat characteristics (wood frequency, wood volume, residual pool depth, percent pool, pool frequency, pool tail fines < 6 mm, median particle size, percent undercut banks, bank angle, and streambank stability) that were collected as part of a stream habitat monitoring program operating across the Interior Columbia River Basin. A primary problem with using monitoring data to assess the extent to which stream reaches have responded to changes in land management policies is that there may be inherent differences in the conditions found in managed and reference catchments. To increase the likelihood that changes detected in our analysis were the result of altered land management practices, we limited our study to stream reaches that had similar physical and environmental settings (Kershner et al. 2004a; Al-Chokhachy et al. 2010a; Chen et al. 2019). In our analysis, we hope not only to assess the effectiveness of new land management policies, but also to identify

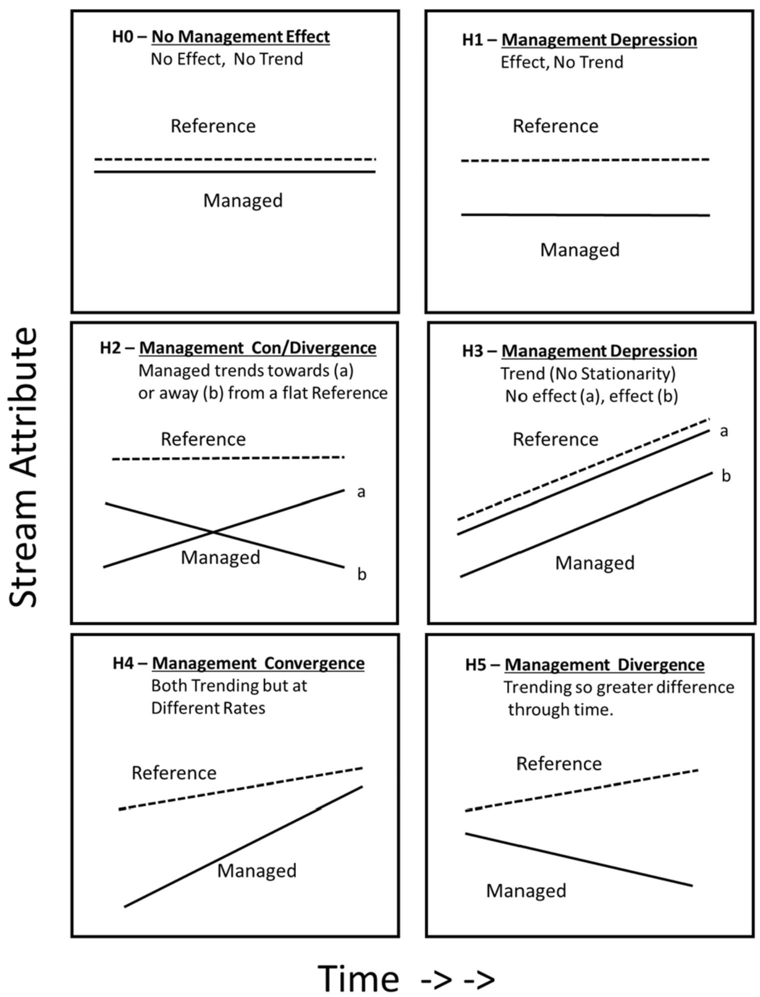

Fig. 1 The *a priori* hypotheses considered for possible responses in stream attribute conditions to the changes in land management policies. We will build models from data collected at reference and managed stream reaches and compare results to these putative models

concerns with evaluating trends in stream habitat conditions based on reference conditions and the assumption of stationarity.

Methods

Sample design

The data we used to determine the status and trends of stream conditions in managed and reference stream reaches were collected as part of a large-scale stream reach monitoring program within the Interior Columbia River Basin (Kershner et al. 2004b). Over time, we anticipated that the direct, indirect, and cumulative effects of the changes in land management policies on federal land should lead to altered stream conditions (Kershner et al. 2004b). To increase the likelihood we would detect these changes, we evaluated low-gradient (0–4%) stream reaches as previous efforts have suggested these types of stream reaches are more sensitive to changes in sediment, debris flow, and other modifications of stream channels that can be caused by land management activities (Montgomery and MacDonald 2002; Fryirs 2017). Additionally, these types of channels are often the most productive salmonid habitats (Roper et al. 1994; Rosenfeld et al. 2000; Buffington et al. 2004) so improving conditions in these areas should have a disproportional positive effect on salmonid populations (Burnett et al. 2007).

Determining the specific stream reaches sampled by this program began by identifying sub-basins (8-digit Hydrologic Unit Codes (HUC)) within the Interior Columbia River Basin with contiguous blocks of public lands that were historically accessed by anadromous fish or occupied by bull trout. We then randomly identified six to eight subwatersheds (12-digit HUC) within each watershed (10-digit HUC) in a sub-basin. Prior to the selection process, we stratified subwatersheds based on whether they were considered managed or reference. For a subwatershed to be considered reference it had to be located in a wilderness area or in a subwatershed with no obvious historic mining, no recent grazing (within 30 years), minimal logging (< 5% of the area), and low road density (< 0.5 km/km^2; Kershner et al. 2004a). All subwatersheds not considered reference were considered managed. To ensure a sufficient sample of reference stream reaches, we randomly selected at least three reference subwatersheds if they were present in a watershed. This stratified design increased the likelihood of sampling reference subwatersheds where they were present, as many watersheds within the Interior Columbia River Basin have few reference subwatersheds. The goal of sampling reference subwatersheds is they served as benchmarks in which to compare the status and trends of stream conditions in managed stream reaches.

Within each randomly selected subwatershed, stream conditions in the lowermost low-gradient stream reach (< 4%) on public land, where the upstream catchment contained at least 50% federal ownership, were evaluated. Given the contiguous pattern of public land ownership, this criteria leads to > 95% of the catchments being federally managed. As the vast majority of the catchment is under federal management, the status and trends in evaluated stream reaches should respond to actions allowed under federal land management policies and natural processes occurring near that stream channel (Batchelor et al. 2015; Nusslé et al. 2017). However, some signal related to catchment scale riparian protections and large-scale disturbances (e.g., fire) will be integrated into that stream reach's condition (Roper et al. 2007). The use of this design results in each stream reach being an independent fluvial unit as catchments does not overlap. Overall, this sample of evaluated stream reaches provides an opportunity to better understand how conditions in low-gradient, wadeable stream reaches on public lands have responded to changes in public land management policies within the Interior Columbia River Basin (Kershner et al. 2004a; Meredith et al. 2014).

The evaluated reach length was 20 times bankfull width with a minimum length of 160 m and a maximum length of 500 m. This project sampled stream reaches in 196 reference and 938 managed catchments. Data collected between 2004 and 2016 were utilized in this study as this time frame had consistent survey protocols and similar annual sample sizes. Most stream reaches were reevaluated on a 5-year rotating panel design, but a subset (25 reference and 25 managed) were sampled annually or biennially from 2004 to 2012, after which sampling reverted to once every 5 years. Once a stream reach was identified for sampling, we reevaluated the same stream reaches in return visits rather than seeking out new sites to reduce the effects of among site variability (Roper et al. 2002). Between 2004 and 2016, these 1134 stream reaches received a total of 3218 evaluations (Table 1).

Table 1 Mean conditions of stream reach and catchments used in this analysis. The first column is the stream habitat attribute of interest. The next two columns are the means and standard deviations (STD) for reference stream reaches. The following two columns are means and standard deviations for all the managed reaches surveyed in the study area. The final two columns represent the means and standard deviations of the managed catchments that were matched to reference catchments

	Reference (*n* = 196)		Managed (*n* = 938)		Matched Managed (*n* = 196)	
Attribute	Mean	STD	Mean	STD	Mean	STD
Elevation (m)	1501	369	1380	424	1503	422
Area (km^2)	36.2	22.9	32.3	22.9	35.9	24.3
Fed management (%)	99.8	1.0	95.1	9.8	97.4	6.5
Precipitation (m)	1.17	0.28	0.87	0.31	1.16	0.30
Forested (% reach)	66	19	53	24	66	19
Bankfull width (m)	7.72	3.01	5.57	2.93	7.44	3.22
Gradient (^{o})	1.89	1.32	1.98	1.19	1.78	1.06
Roads density (k/km^2)	0.06	0.12	1.36	1.07	0.90	0.99

Stream habitat conditions

At each stream reach, we evaluated ten stream attributes shown to be important to the growth and survival of salmonids (Hicks et al. 1991; Rosenfeld et al. 2000) and sensitive to changes in land management activities (Woodsmith and Buffington 1996; Kershner et al. 2004a; Al-Chokhachy et al. 2010a). These attributes were wood frequency, wood volume, residual pool depth, percent pool, pool frequency, pool tail fines (< 6 mm), median particle size, percent undercut banks, bank angle, and streambank stability (Table 2).

To estimate wood frequency (pieces/km), we counted pieces of wood exceeding 10 cm in diameter and 1 m in length within the bankfull stream channel. To obtain wood volume from wood count data, we applied the following formula, $\pi r^2 h$, where r was the radius of each wood piece one-third up from its base and h was the length of each qualifying piece. We scaled wood volume to m^3/km. We estimated the three pool habitat metrics by measuring the length and depth of each pool within a reach and from these data determined average residual pool depth (maximum depth minus depth at pool tail crest), percent of the reach length in pool habitat, and pool frequency (number of pools/reach length). We obtained an estimate of the percent fine sediment < 6 mm evaluating fine sediment within the tail out of each identified pool in the reach using a grid approach

Table 2 Stream habitat attributes evaluated in this study and the expected direction of change that would represent an improvement in that stream condition for salmonids of the Pacific Northwest

Stream attribute	Desired direction of trend	Source
Wood frequency	More	Beechie and Sibley 1997; Rosenfeld et al. 2000
Wood volume	More	Beechie and Sibley 1997; Rosenfeld et al. 2000
Residual pool depth	Deeper	Lisle 1987; McIntosh et al. 2000
Pool frequency	Higher	McIntosh et al. 2000
% pool	More	Magilligan and McDowell 1997
Median particle size	Larger	Montgomery and MacDonald 2002
% fines (< 6 mm)	Less	Chapman 1988, Montgomery and MacDonald 2002
Bank stability	Higher	Myers and Swanson 1992
Bank angle	Steeper	Knapp and Matthews 1996
% undercut banks	More	Knapp and Matthews 1996

(Bunte et al. 2012). We then averaged across the pools in the reach. We measured substrate particle sizes (*b* axis) at 10 equidistant points across the active stream channel at 10 systematic transects for estimates of median particle size in the stream reach. Streambank characteristics were assessed on both banks at approximately 20 equally-spaced transects through the stream reach. At these locations ($n \approx 40$), we determined if the bank was undercut (bank with angles < 90 degrees), the bank angle, and streambank stability. A streambank was considered stable, if at bankfull flows, the sampled location was subject to limited erosion due to the presence of coarse material (e.g., wood or cobble) or cohesive vegetation. We averaged all measurements taken in a stream reach to estimate percent of the reach with undercut banks, streambank angle, and streambank stability. A complete description of these variables and their field methods has been published previously (Al-Chokhachy et al. 2010a; Heitke et al. 2011).

Determining stream reaches used for analysis

The intent of this monitoring program was to determine how change in federal management policies affected the direction and rate of change in stream habitat attributes within the Interior Columbia River Basin (Kershner et al. 2004b). The biggest difficultly in making these comparisons is federal land management activities are generally concentrated in more easily accessed areas, while reference catchments tend to be more distant from population centers, higher in elevation, and receive greater precipitation (Table 1). Differences in the average catchment conditions above managed and reference stream reaches suggest incorporating all evaluated managed stream reaches into our analysis could bias our understanding of the status and trends (Reynoldson and Wright 2000; Chessman et al. 2008; Bailey et al. 2014) and conflate the effects of land management with differences in environmental settings (Irvine et al. 2015). To reduce the possibilities of these outcomes, we stratified our managed stream reaches and catchments so that those used in our analysis occupied environmental settings similar to reference sites.

Our goal was to identify the subset of managed stream reaches and catchments most similar to reference stream reaches and catchments. We did this using the propensity score approach described by d'Agostino (1998). Propensity scores were determined using a logit model where reference and managed catchments were the binary response variable. This approach then seeks to minimize the differences in important environmental attributes within these two types of catchments. The environmental attributes we incorporated were elevation, catchment area, annual precipitation, and percent of the area near the evaluated stream reach that was forested (Al-Chokhachy et al. 2010b). We determined site elevation at the bottom of the evaluated stream reach and catchment area (km^2) was the area above that point. Annual precipitation was the 30 year (1971–2001) weighted average (by area) of the precipitation grids (16 km^2) that intercepted each catchment (PRISM 2004). The percent of the riparian area that was forested was determined by buffering the stream segment 90 m on both sides from the bottom of the evaluated stream reach upstream for 1 km. Within that area, all tree-dominated vegetation classes identified using LANDFIRE (Rollins and Frame 2006) were considered forested.

Based on propensity scores, the 196 managed stream reaches whose environmental settings were most similar to the 196 reference stream reaches were used in this analysis. By limiting the number of managed reaches, we increased the similarity of the environmental conditions and variance in stream conditions (Table 1, Fig. 2) and addressed assumptions required for statistical comparisons. In making the choice to increase the similarity of managed and reference stream reach and catchment conditions, we lowered the number of managed stream reaches from 938 to 196. The final data set used in this analysis included 392 stream reaches that had been visited 1158 times.

Analysis of status and trend

Our primary objective in these comparisons was to determine which of the hypotheses presented in the introduction (Fig. 1) best represented the status and trends of the evaluated stream attributes. To address this objective, we determined if there was a significant difference in management history (managed, reference) and/or a significant trend. If we identified no difference in condition and no trend, then hypothesis H0 best represented that stream attribute. An attribute, where we found significant differences in condition but no trend, would be best described by H1. If there was no difference in condition but there was a trend, then these data reflected H3a. Stream attributes with a consistent and significant difference and a significant trend would

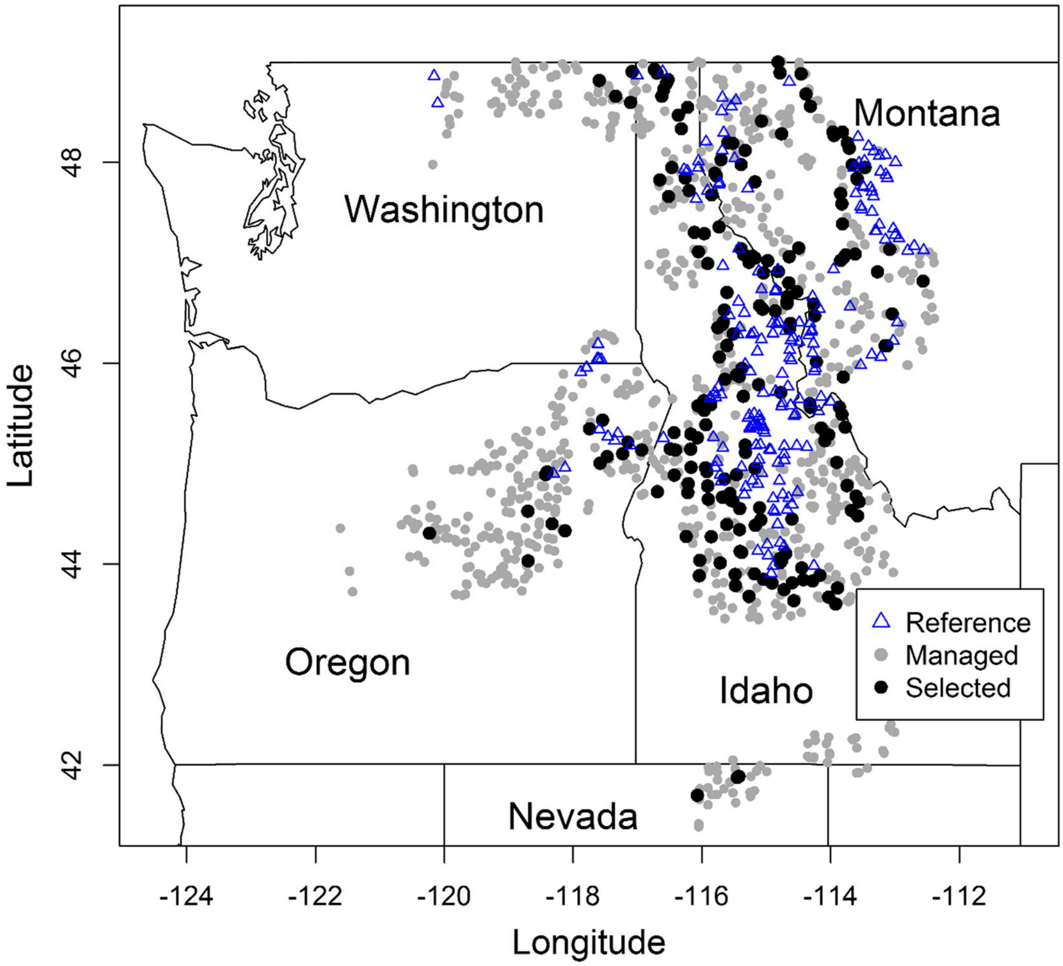

Fig. 2 Map of the locations of sampled stream reaches. The open triangles represent reference reaches while the circles represent managed reaches. The black circles are the managed stream reaches selected for analysis while the remaining gray circles were excluded from analysis

be best represented by hypothesis H3b. The final possibilities were there was a significant interaction between management history and trend. When data suggested stream habitat conditions were converging, then either hypothesis H2a or H4 best explained the data. If stream habitat conditions were diverging, then H2b or H5 would best describe the data.

In order to improve our ability detect status and trends, we incorporated covariates to reduce variability not related to changes in land management policies. A good example of why we included this step can be seen in the negative relationship between stream gradient and the percent of the stream reach consisting of pools (see Fig. 4 of Al-Chokhachy et al. 2010a). Without accounting for these relationships, this variation becomes a component of the unexplained error in the model. The covariates we evaluated for inclusion in our models included precipitation, elevation, catchment area, percent of the reach that was forested, bankfull width, and gradient (Kershner et al. 2004a). Methods used to determine precipitation, elevation, catchment area, and percent forested have been described previously. Bankfull width was the average of measured bankfull widths recorded at approximately 20 equally-spaced cross-sections within the stream reach. Gradient was a field measurement of the evaluated stream reach's change in the water surface elevation divided by its length. To reduce the effect of observer variation in the field measurement of bankfull width and gradient, values used in our analysis were the average of the multiple independent visits through time to each stream reach.

We determined the best linear model for each of the 10 stream attributes using backward selection methods. To decrease the likelihood of failing to reject the null hypothesis when the null hypothesis was false (type II error), we set $p < 0.1$ for including a term in the model. This choice reflects the limitation of building models based solely on p values and the need to discuss uncertainty and limitation associated with any selected model (Cade 2015; Wasserstein et al. 2019). In constructing these models, we assessed the inclusion of management history (reference versus managed), trend, an interaction between management history and trend, and our set of environmental covariates. If all components entered the model, the full model would be as follows:

$$\gamma_{ijy} = \mu + \alpha_i + \tau_y + (\alpha\tau)_{iy} + \nu_{(1-6)} + \delta_{ij} + \varepsilon_{ijy}$$

where γ is one of the ten stream attributes we used as response variables, μ is the overall mean, α_i is the effect of the ith treatment (managed or reference), τ_y is the continuous variable reflecting the year data were collected, $\alpha\tau$ is the interaction between the ith treatment and time y, and $\nu_{(1-6)}$ represents the possible inclusion of up to six covariates (bankfull with, gradient, elevation, catchment area, annual precipitation, and percent forested). These are the fixed parameters of the model. The random effect is δ_{ij}, and is associated with the jth stream reach in the ith treatment. For the 382 stream reaches treated as random effects, we evaluated whether each site had similar trends and unique intercepts or unique trends and intercepts (Galecki and Burzykowski 2013). The last value, ε, is random error associated with the jth subject in treatment i with trend y not accounted for in the model. To help evaluate the strength of the best models, we present a coefficient of determination (R^2) for mixed models (Nakagawa et al. 2017).

To address the assumptions of normality while maintaining interpretability of results, we log-transformed wood frequency, wood volume, residual pool depth, median particle size, and pool tail fines. In transforming these variables, results should be seen as multiplicative rather than additive (Limpert et al. 2001). This means that stream attributes that were log-transformed and have parallel trends between managed and reference reaches do not maintain a constant numeric difference, but instead have the same rate of change. Additionally, we describe results from back-transformed stream attributes as medians rather than means as this value more closely reflects outcomes of this transformation (Limpert et al. 2001). Analysis was conducted in R using the base package (R Core Team 2018), MatchIt (Ho et al. 2011), lme4 (Bates et al. 2015), ggplot2 (Wickham 2016), effects (Fox 2003), and lmerTest (Kuznetsova et al. 2017).

Results

The use of propensity analysis greatly increased the environmental similarity of the stream reaches used in this analysis (Table 1, Fig. 3) and led to reference and managed stream reaches being geographically interspersed (Fig. 2). This approach eliminated most managed stream reaches sampled in eastern Oregon, eastern Washington, and southern Idaho from our analysis. The stream reaches excluded often had starkly different environmental condition than those found in reference stream reaches, including lower elevations, less precipitation, higher percentages of private lands, and more non-forested riparian areas (Table 1, Fig. 3). By eliminating these managed stream reaches from our analysis, the intensity of land management activities as indicated by our surrogate (i.e., road density) dropped by about a third (Table 1).

The trends observed for wood frequency and volume suggested the total amount of wood differed between managed and reference stream reaches, but was increasing at similar rates over the study period (H3b, Fig. 1; see Fig. 4, Table 3). The median number of wood pieces was lower in managed stream reaches, but increased over the duration of the study from 151 pieces per km in 2004 to 204 in 2016. This increase cut in half the initial difference in the frequency of wood in managed and reference stream reaches as reference reaches started with 246 pieces. Over the same time period, however, wood frequency in reference reaches increased to 333. The difference and trend in wood volume was similar to the pattern we observed for wood frequency (Fig. 4).

The two attributes pertaining to streambed substrate, median particle size and pool tail fines (< 6 mm), provided the greatest evidence that managed stream conditions were improving relative to reference reaches (Fig. 4). The median particle size in reference reaches was getting smaller while it was getting larger in managed reaches. This trend reflects a divergence and lack of stationarity (H5, Fig. 1), but suggests conditions in reference reaches were declining relative to what would be considered quality salmonid habitat, while conditions in managed reaches were improving. We saw a similar divergence in the conditions of pool tail fines where the managed stream reach conditions were improving (numerically declining) but conditions in reference stream reaches remained nearly constant (H2b, Fig. 1). That conditions were

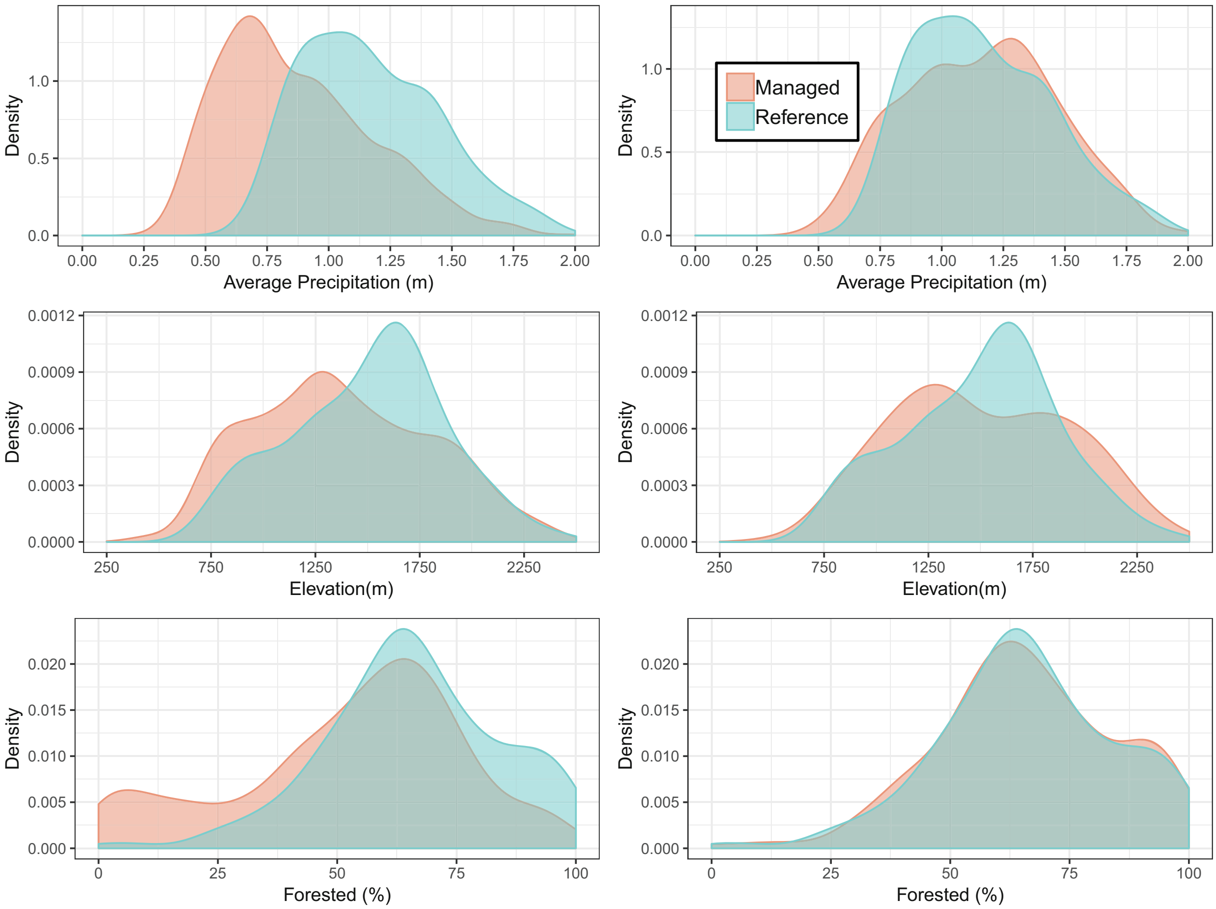

Fig. 3 Comparisons of the distribution of three covariates used in our analysis; precipitation, elevation, and percent of the area near the evaluated reach that was forested. The left panel include all managed sites (n = 938) while the right panel are the distributions of the 196 managed catchments used in our analysis. Data from reference sites for both panels are the same (n = 196)

improving in managed stream reaches in a manner that differed from the trends in reference reaches supports the hypothesis that changes in management policies has had a positive effect on these streambed sediment attributes.

There was evidence of a land management effect on residual pool depth but conditions at managed and reference stream reaches were neither trending nor converging through time (H1, Fig. 1; see Fig. 4, Table 3). The magnitude of differences was consistent with previous work done in this region that suggested pools were deeper in reference stream reaches (Kershner et al. 2004a).

Two stream habitat attributes were trending towards improved habitat conditions for salmonids (Table 3, Fig. 4): pool frequency and bank stability. For both attributes, the trends were similar in managed and reference stream reaches and the differences in the conditions were not significant (H3a, Fig. 1). In contrast, the direction of the trend in streambank angles could be seen as adversely affecting salmonid populations, but trends and status did not differ significantly between managed and reference stream reaches (H3a).

Although the percent of the streambanks with undercuts was slightly higher in reference stream reaches, it was not significantly different from managed reaches and there was no significant trend (H0, Fig. 1). The same pattern was seen for the percent of the stream reach that was pool habitat (H0).

Estimating status and trend for all ten stream attributes benefited from the inclusion of covariates (Table 3). Wood frequency, wood volume, pool depth, and median particle size all increased as bankfull widths increased, while percent pool, pool frequency, pool tail fines, and streambank stability decreased. Wood volume, median particle size,

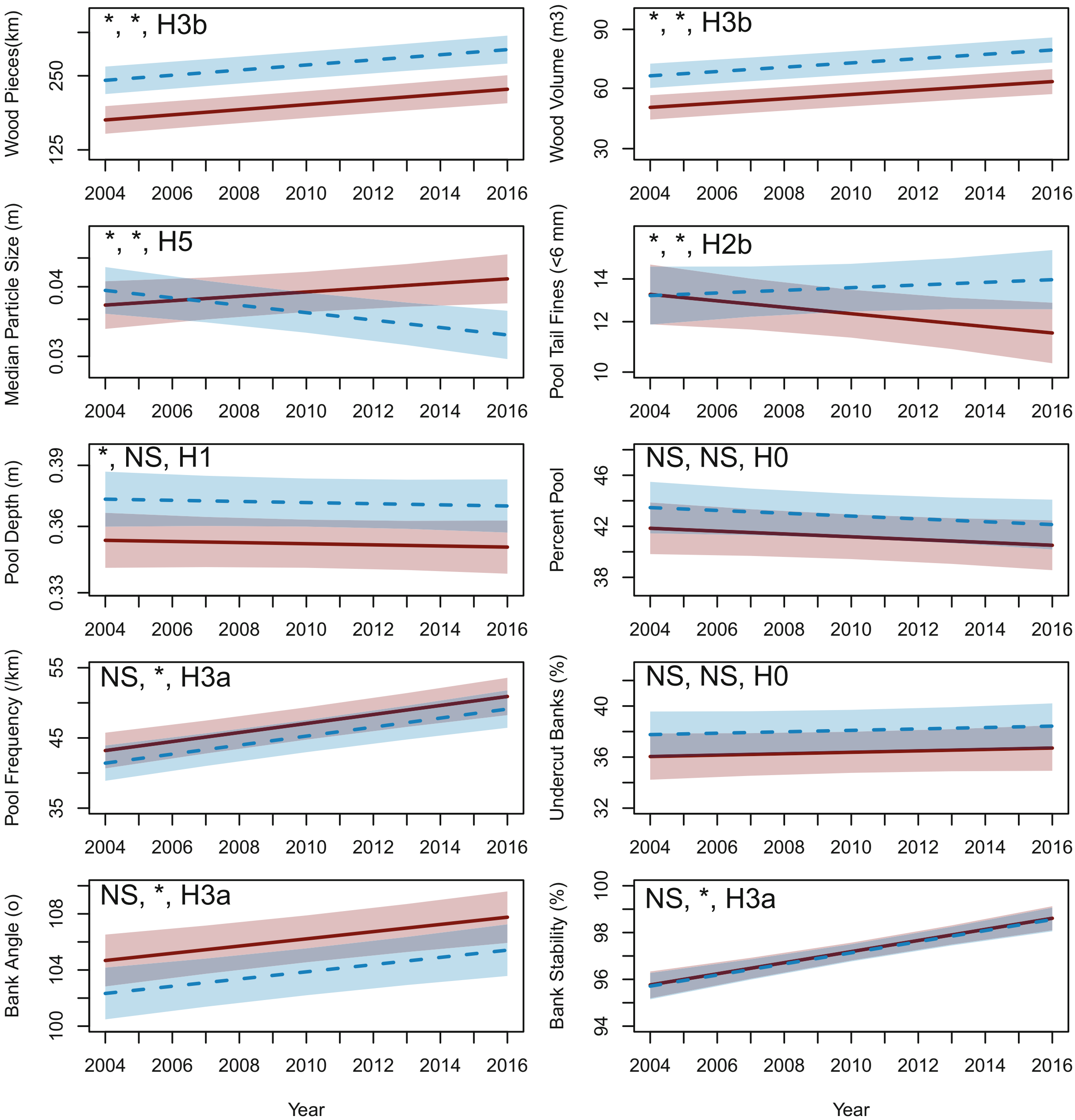

Fig. 4 Status and trends of the ten stream attributes at the mean values for the covariates in the model (see Table 3). The solid line represents trends in managed sites while the dashed line represents reference site trends (with 90% confidence intervals). The first value in the text in the upper left of the box for each attributes represents mean difference in the status of manage and reference reaches; NS is not significant and * for significant. The second value represent the trends, again with NS and *. The final value is the model the status and trend that stream attribute best reflects (see Fig. 1)

bank angle, and streambank stability increased as gradient increased, but pool depth, percent pool, pool frequency, pool tail fines, and percent of the streambanks that were undercut all decreased. Each of these relationships reflects the expected effect of stream power on stream attributes (Kershner et al. 2004b). Similarly, we found wood frequency, wood volume, and pool frequencies all increased as the percent of the riparian zone that was forested increased.

Table 3 The best fixed effect models for the 10 stream attributes evaluated. In the trend columns, M stands for managed and R is for reference. Entries can be NS (not significant, $p > 0.1$), a + which suggests a positive trend or a − suggesting a negative trend. If symbols are different for M and R, then there is a significant interaction in trend. The next section covers the six covariates; BF stands for bankfull, Elev for elevation, Area for catchment area, Precip for annual precipitation, and Forested as the percent of the stream buffer within 1 km of the bottom of the stream reach this is forested. If a covariate is included in the model there is a + or − which indicates the covariates relationship to the stream attribute. An NS means it is not in the best model. The two columns under model fit indicate the hypothesis from Fig. 1 that best represents that stream attribute and the portion of the variability explained by the fixed effects in the model (R^2)

	Trend		Covariate						Model fit	
Stream attribute	M	R	BF	Grad	Elev	Area	Precip	Forest	Hypotheses	R^2
Wood frequency	+	+	+	NS	NS	−	−	+	H3b	0.19
Wood volume	+	+	+	+	−	−	−	+	H3b	0.22
Particle size	+	−	+	+	NS	+	+	NS	H5	0.47
Fines < 6 mm	−	NS	−	−	NS	−	−	NS	H2b	0.32
Pool depth	NS	NS	+	−	+	−	NS	−	H1	0.39
Pool percent	NS	NS	−	−	NS	−	NS	NS	H0	0.38
Pool frequency	+	+	−	−	−	−	NS	+	H3a	0.51
Percent undercut	NS	NS	NS	−	+	−	NS	NS	H0	0.18
Bank angle	+	+	NS	+	−	+	NS	NS	H3a	0.21
Bank stability	+	+	−	+	NS	+	+	NS	H3a	0.05

Discussion

The status and trends we describe for stream conditions on public lands throughout the Interior Columbia River Basin provide evidence that changes in federal land management policies in the 1990s (USDA/USDI 1994, 1995; USDA 1995) likely played a meaningful role in maintaining or improving habitat conditions important to salmonids. In managed catchments, conditions of nine of the ten stream attributes were either stable or improving. The only attribute declining in condition relative to its value to salmonids was streambank angle. The trend for streambank angle in managed catchments, however, was parallel to those in reference reaches suggesting the mechanisms driving changes in this stream attribute's conditions were likely related to trends in environmental conditions (Gresswell 1999; Brunsden 2001). While our results support the conclusion that changes in land management policies likely played an important role in improving stream conditions, the patterns of these relationships raised a number of questions on how stream habitat assessment results should be interpreted.

The clearest evidence that changes in land management policies affected trends in stream conditions were seen in the two streambed sediment attributes: median particle sizes and pool tail fines. That we detected a response in streambed sediment metrics was not surprising given we measured these attributes in low-gradient stream reaches sensitive to change (Montgomery and MacDonald 2002) and these attributes have been shown to respond relatively quickly to natural disturbances and land management activities (Potyondy and Hardy 1994; Al-Chokhachy et al. 2016). Because this is a field study, it is difficult to unequivocally equate this correlation as causation. Our choices to only compare similar managed and reference catchments, to reduce unexplained variation with covariates, and to incorporate random sampling, however, greatly increased the likelihood the differences we observed were due to changes in land management activities and not spurious correlations (Holland 1986).

We found divergent trends between management histories for the percent of the pool tails covered by fine materials (< 6 mm) and median particle sizes. The slight decrease in median particle size and stable percent of the pool tails that were fines in reference reaches were most likely influenced by additional sediment inputs caused by larger and more intense fires (Westerling et al. 2006; Littell et al. 2009) continuing to enter streams to replace sediment being mobilized downstream (Roper et al. 2007; Wagenbrenner and Robichaud 2014). These processes nearly balanced out so streambed sediment conditions important to salmonids declined only slightly or non-significantly in reference reaches. The trends towards increased median particle size and fewer pool tail fines in managed stream reaches suggest efforts to limit sediment inputs from timber harvest, road construction, improved road maintenance, and by decommissioning road segments have likely led to streambed substrate conditions in managed catchments that are more suitable to salmonids today than they were two decades ago (Furniss et al. 1991; Cristan et al. 2016). As streambed sediment size plays an important role in salmonid occupancy (Al-Chokhachy et al. 2010b) and spawning success (Chapman 1988; Buffington et al. 2004), the trends in these stream habitat metrics should ultimately increase the capacity of managed stream reaches to produce salmonids.

Increases in wood frequency and wood volume further support the hypothesis that changes in land management policies have improved stream habitat conditions. Trends and comparisons to reference reaches, however, suggest climate change and fire exclusion may also be influencing the observed pattern. That managed streams had approximately a third less wood than reference streams at the beginning of this study (2004) likely reflects historic land management activities that had greatly reduced the amount of wood reaching and being maintained in managed streams (Ralphs et al. 1994; Kershner et al. 2004b; Steel et al. 2016). Differences in wood frequency and volume between managed and reference catchments at the beginning of this study were meaningful but not insurmountable given the multiplicative nature of the observed trend (i.e., the response variables were log-transformed). If the rate of increase observed over the study period was maintained in managed stream reaches and conditions in reference reaches had been static, the initial wood frequency deficit in managed streams could have been eliminated by 2024. The ability to close this gap is based on the assumption that the wood frequency and volume in reference stream reaches were stable through time; which they were not. Instead, the amount of wood in reference stream reaches was increasing at the same rate as in managed reaches.

Increases in wood frequency and volume in reference stream reaches are likely due in part to higher tree densities in the unmanaged portions of the landscape because of the Forest Service's historic firefighting efforts (Keane et al. 2002). Higher tree densities combined with higher tree mortality related to fires, beetle kill, and climate change (Gresswell 1999; Westerling et al. 2006; van Mantgem et al. 2009) likely all played a role in increasing the amount of wood in reference stream reaches. These same factors also affect managed catchments, but wood recruitment is limited in some managed stream reaches where road prisms are in the stream corridors (Meleason et al. 2003; Meredith et al. 2014) or where riparian areas were previously harvested and have not yet regrown (Burton et al. 2016).

The only stream attribute we found that reflected the putative management effect was residual pool depth where managed reaches maintained a consistent deficit relative to deeper pools in reference reaches (H1; McIntosh et al. 2000; Kershner et al. 2004a). Given the observed increase in wood loading, we expected increasing pool depths across all the evaluated stream reaches (Dahlström and Nilsson 2004). Our failure to detect this trend could be due to the complexity of interactions related to large wood inputs and pool depth or simply the pattern of precipitation and stream flows over the study period (see next paragraph). Regardless of the specific mechanisms, this suggests if we are to detect changes in pool depth due to changes in management policies, it may take more than a couple decades.

Trends for two of the three streambank attributes, streambank angle, and bank stability do not appear wholly driven by management history as they are similar and not significantly different (hypothesis H3a). One possible reason why these attributes were trending in a similar direction may be related to the pattern in precipitation and stream flows over the study period. The lowest annual (water-year) precipitation occurred during the first visits to the stream reaches (2004–2009) while there was generally above average precipitation occurring during the last 6 years (2010–2016; WestMap 2017). Increasing precipitation could foster vegetative growth that should improve streambank stability (Eaton and Giles 2009), but exacerbate winter and spring erosion that increases streambanks angles. We posit this explanation not because we're sure it is the correct mechanism to explain these trends, but because it represents the possibility of detecting linear trends in stream conditions associated with short-term climatic oscillations such as those due to the El Niño Southern Oscillation (Rodo et al. 1997) that may be nested within longer-term trends in stream habitat conditions related to climate change (Honea et al. 2016).

The need to parse discordant and concordant sources of variation associated with environmental fluctuations increases the time it takes for aquatic monitoring programs to detect trends due to management actions (Larsen et al. 2004). Our use of reference reaches provides insight that much of the observed positive trends in managed stream habitat conditions were related to concordant environmental variation with differences in the initial state of some attributes, likely due to differences in management history. Our evaluation of trends in stream habitat concurrently in managed reaches and reference reaches helped guard against conflating the effects of management policies with background environmental trends. For example, in the absence of reference data, a possible conclusion relative to the trend in streambank angle may have been that changes in management policies had been ineffective. That the trend for this attribute was the same in reference reaches, counters that argument.

The lack of independence between the environmental setting and management intensity within a catchment will continue to make it difficult to isolate the effects of land management practices on stream attributes across Forest Service/BLM managed lands within parts of the Interior Columbia River Basin. It was clear road densities in managed sites not included in our analysis were higher than those that were included (Table 1). Given the strong positive relationship between road density and timber harvest (Dose and Roper 1994), it is likely the managed catchments used in our analysis were subject to less intensive timber harvest. Furthermore, many managed sites were drier so could be rangeland catchments subject to higher grazing intensities (Irvine et al. 2015; Swanson et al. 2015). Our choice to eliminate the majority of the evaluated managed stream reaches was because there were no comparable reference reaches which solicit the question of how should the putative status and trend of many managed stream reaches be determined?

Public land managers must recognize the lack of analogs for determining desired conditions in many managed catchments does not negate their responsibility to address habitat needs of aquatic species (Hiers et al. 2012). To address this concern, it will be necessary to continually measure and model how changes to land management activities affect stream channel conditions and manage towards a set of conditions that protects the species of interest (Batchelor et al. 2015; Justice et al. 2017; Nusslé et al. 2017). Determining goals for stream conditions in heavily managed areas with species-at-risk will require transparency and public input to define conservation targets and restoration success (Palmer et al. 2005; Kershner and Roper 2010; Wiens and Hobbs 2015).

This may be achieved by focusing on restoring stream and riparian characteristics that protect native biodiversity, provide ecological services, and are achievable in that specific land management setting (Balaguer et al. 2014; Higgs et al. 2014). Increasing short-term resilience by restoring stream and watershed processes degraded by past management activities provide a good interim approach (see Palmer et al. 2005). Setting stream habitat objectives that are unmoored from conditions in reference catchments will require a strong partnership between research, management, and the public. If such an approach is properly implemented, it has the potential to increase ecosystem resilience while continuing to provide a wide array of ecological and economic outcomes and outputs (Golladay et al. 2016). Misapplication in defining desired conditions combined with an altered disturbance regime, however, could lead to rapid change in stream habitat conditions and rapid changes in a species distribution and/or population sizes (Isaak et al. 2018).

Conclusions

Our analysis indicates the status and trends of stream conditions in a subset of managed catchments, as measured by their value to salmonids and compared to reference conditions, were generally improving within the study area. Improvements in stream conditions suggest the Forest Service and BLM are addressing their legal mandate to implement conservation actions that improve the habitat of ESA listed salmonid species. This improvement is likely in part due to more conservative riparian management standards implemented in federal land management plans in the Pacific Northwest (Boisjolie et al. 2017). In addition to limiting activities in 100 m wide riparian habitat conservation areas on both sides of fish bearing streams, federal managers have put in place best management practices to limit sediment input to streams from roads (Al-Chokhachy et al. 2016; Sosa-Pérez and MacDonald 2017), and have greatly reduced the amount of timber harvested from federal lands in the region (Adams et al. 2006). Given the conservative nature of these 20-year-old management plans, it should not be surprising that many stream conditions have responded positively to these changes over this timespan.

Despite the benefit of studies such as this one, insufficient effort has been directed at monitoring the outcomes of large-scale state and federal decisions intended to improve aquatic conditions (Bernhardt et al. 2005; Anlauf et al. 2011). The lack of large-scale monitoring efforts has made it difficult to determine what level of change in land use policies is necessary to protect or improve aquatic conditions or is worth the economic cost of their implementation (Keiser et al. 2018). There remains a need for future studies to elucidate which policy changes enacted by federal land management agencies have the largest benefit to riparian and stream conditions at the lowest economic cost.

Federal land management agencies altered planning direction in the mid-1990s, in part to maintain or improve the quality of aquatic systems for salmonids (USDA/USDI 1994; USDA/USDI 1995; USDA 1995). We used data collected within the Interior Columbia River Basin to show it was possible and practicable to detect trends in the conditions of stream attributes relevant to salmonid productivity within a 20-year time frame. This monitoring effort responds to the public's demand for greater accountability. Furthermore, it provides affirmation that reducing or altering how resource extraction efforts are conducted near streams has fostered the conservation of habitats that sensitive and ESA listed aquatic species require. That federal land management agencies were able to collect relevant stream habitat data at large spatial scales, over a relatively short time frame, to meet regulatory requirements reinforces the value of large-scale aquatic monitoring programs (Lovett et al. 2007).

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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