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Forest management impacts on stream integrity at varying intensities and spatial scales: Do abiotic effects accumulate spatially?

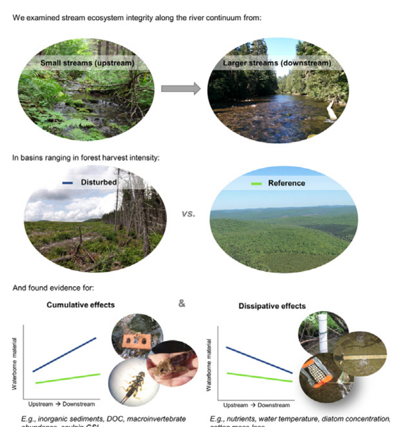
Maitane Erdozain [a,*], Karen A. Kidd [a,b], Erik J.S. Emilson [c], Scott S. Capell [c], David P. Kreutzweiser [c], Michelle A. Gray [d]

[a] Canadian Rivers Institute and Biology Department, University of New Brunswick, 100 Tucker Park Road, Saint John, New Brunswick E2L 4L5, Canada
[b] Department of Biology, School of Earth, Environment and Society, McMaster University, 1280 Main St. W., Hamilton, Ontario L8S 4K1, Canada
[c] Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, 1219 Queen St. East, Sault Ste. Marie, Ontario P6A 2E5, Canada
[d] Canadian Rivers Institute, Faculty of Forestry and Environmental Management, University of New Brunswick, 28 Dineen Drive, Fredericton, New Brunswick E3B 5A3, Canada

HIGHLIGHTS

- Longitudinally cumulative effects of forestry detected for inorganic sediments
- Longitudinally dissipative effects for temperature, nutrients, organic sediments
- Abiotic impacts of forestry reported in small streams also extend to larger systems

GRAPHICAL ABSTRACT



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ABSTRACT

Though effects of forest harvesting on small streams are well documented, little is known about the cumulative effects in downstream systems. The hierarchical nature and longitudinal connectivity of river networks make them fundamentally cumulative, but lateral and vertical connectivity and instream processes can dissipate the downstream transport of water and materials. To elucidate such effects, we investigated how a suite of abiotic indicators changed from small streams to larger downstream sites ($n = 6$) within three basins ranging in forest management intensity (intensive, extensive, minimal) in New Brunswick (Canada) in the summer and fall of 2017 and 2018. Inorganic sediments, the inorganic/organic ratios and water temperatures significantly increased longitudinally, whereas nutrients and the fluorescence index of dissolved organic carbon (DOC; indication of terrestrial source) decreased. However, some longitudinal trends differed across basins and indicated downstream cumulative (inorganic sediments, the inorganic/organic ratios and to a lesser extent DOC concentration and humification) as well as dissipative (temperatures, nutrients, organic sediments) effects of forest management. Overall, we found that the effects previously reported for small streams with managed forests also occur at downstream sites and suggest investigating whether different management practices can be used within the extensive basin to reduce these cumulative effects.

* Corresponding author.
E-mail address: maitane.erdozain@unb.ca (M. Erdozain).

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1. Introduction

Headwater streams constitute >80% of stream networks (Leopold et al., 1964) and are considered the capillaries of the landscape, with most of the water and material exchange happening in these small streams (Gomi et al., 2002). At the same time, headwater streams are the main source of water, organic matter, nutrients and sediments for downstream systems (Leibowitz et al., 2018, Fig. 1a) and are therefore key in maintaining the larger river ecosystems upon which humans and many other species depend (Meyer and Wallace, 2001; Freeman et al., 2007; Wohl, 2017). But the connectivity that ensures the ecological integrity of river networks also makes them vulnerable to catchment disturbance by facilitating the flow of impacts along the river continuum (Freeman et al., 2007; Wipfli et al., 2007). This is because the intrinsically hierarchical nature and longitudinal hydrological connectivity of river networks makes them fundamentally cumulative, i.e., as more water converges longitudinally, materials dissolved or suspended in water accumulate (Fritz et al., 2018).

In addition to the longitudinal connectivity, lateral and vertical connections and instream processes also affect the transport of water and materials and, thus, the cumulative nature of fluvial networks (Bencala et al., 2011; Covino, 2017). For example, lateral connectivity (e.g., floodplain inundation) can favour the processing of organic carbon and its redirection to the atmosphere rather than downstream (Battin et al., 2009; Erdozain et al., 2020a). The vertical connectivity of hyporheic exchange can reduce nitrogen export by offering denitrification hotspots (Mulholland et al., 2008). In addition, there is also a temporal dimension that influences processes as losses occur during transport (e.g., dissolved organic carbon photoreduction, nutrient uptake). Obstacles along the network (e.g., log jams) can also reduce sediment transport downstream (Elosegi et al., 2017). These examples of sink functions (Leibowitz et al., 2018, Fig. 1a) illustrate that the degree to which streams fuel downstream systems depends on the extent of such transformations and/or storage of materials (Covino, 2017). This, in turn, should affect how disturbances to headwater streams manifest downstream. For example, inorganic sediments resulting from forest disturbance are expected to propagate further downstream than organic sediments or nutrients since the latter can be biologically or chemically transformed during downstream transport (MacDonald and Coe, 2007). However, little is known about the larger-scale

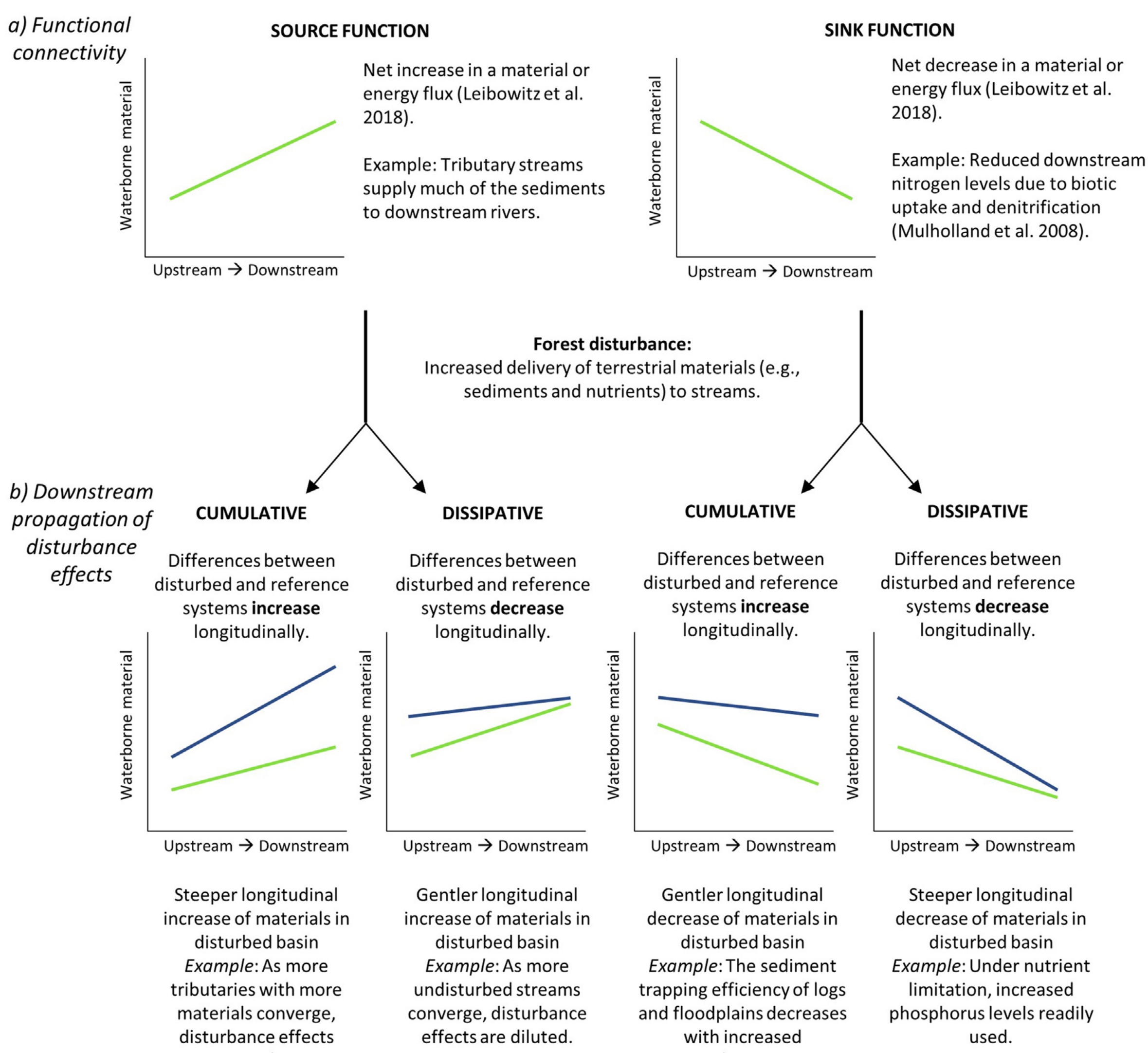

Fig. 1. Diagram describing the theoretical framework used in this study to interpret longitudinal trends of waterborne material concentrations (y-axis) between streams and downstream waters (x-axis) to elucidate cumulative effects. This includes: a) the two main types of functional connectivity considered in this study, and b) the comparison of longitudinal trends between a reference (green line) and disturbed (blue line) fluvial system.

consequences of disturbing the landscape capillaries (Gomi et al., 2002; Freeman et al., 2007). Based on this complexity and multidimensionality, there is a need to assess how catchment disturbances affecting headwater streams are integrated in downstream systems (MacDonald and Coe, 2007).

Forest harvesting and management cause catchment disturbances known to impact stream ecosystem integrity. Tree removal results in greater and faster water delivery to streams after rain events (Moore and Wondzell, 2005; Buttle et al., 2009). This can lead to more waterborne materials (e.g., sediments, nutrients, cations) being delivered to streams after harvesting, which is exacerbated by roads, soil disturbance by machinery, reduced soil stability and enhanced biogeochemical processes in soils (Croke and Hairsine, 2006; Kreutzweiser et al., 2008; Webster et al., 2015; Erdozain et al., 2018). Stream water temperatures and thermal diel fluctuations tend to increase after canopy removal as more sunlight penetrates the water and soils (Moore et al., 2005). These abiotic changes, in turn, affect biological communities and processes in streams (Kreutzweiser et al., 2013; Richardson and Béraud, 2014; Erdozain et al., 2018). To mitigate such impacts, forestry policies, certifications and practitioners have implemented numerous best management practices, including the application of riparian buffer zones (i.e., streamside restricted-harvest forest reserves) and guidelines for stream crossings and road construction (Schilling, 2009; McDermott et al., 2010). Although they are mostly effective, our understanding is mainly based on reach-scale effects in small streams (Broadmeadow and Nisbet, 2004; Cristan et al., 2016).

Little is known about the cumulative effects of forest management on downstream systems and whether best management practices designed to protect headwater streams are effective at larger scales (Freeman et al., 2007; Wipfli et al., 2007; Kreutzweiser et al., 2013). Considering that more materials and energy reach streams and that longitudinal connectivity may be enhanced (due to increased post-rain flows), cumulative effects of forest harvesting are possible and have indeed been indicated in the few studies done to date. Charbonneau (2019) reported harvesting-induced cumulative effects on the organic content of sediments and mercury concentrations in water and macroinvertebrates. Martel et al. (2007) and Deschênes et al. (2007) found that logging impacted benthic macroinvertebrates and salmon only at larger spatial scales (>8 km scale), which they attributed to the accumulation of sediments from multiple headwaters in downstream reaches. Disturbance-related changes in the biological community could, in turn, further affect the downstream movement of detritus and nutrients (Harvey et al., 2016). Overall, there is a need to understand how forest management effects change from headwaters to downstream reaches, especially considering that hydrological connectivity and the associated transport of materials and energy are dependent on the environmental context (Fritz et al., 2018).

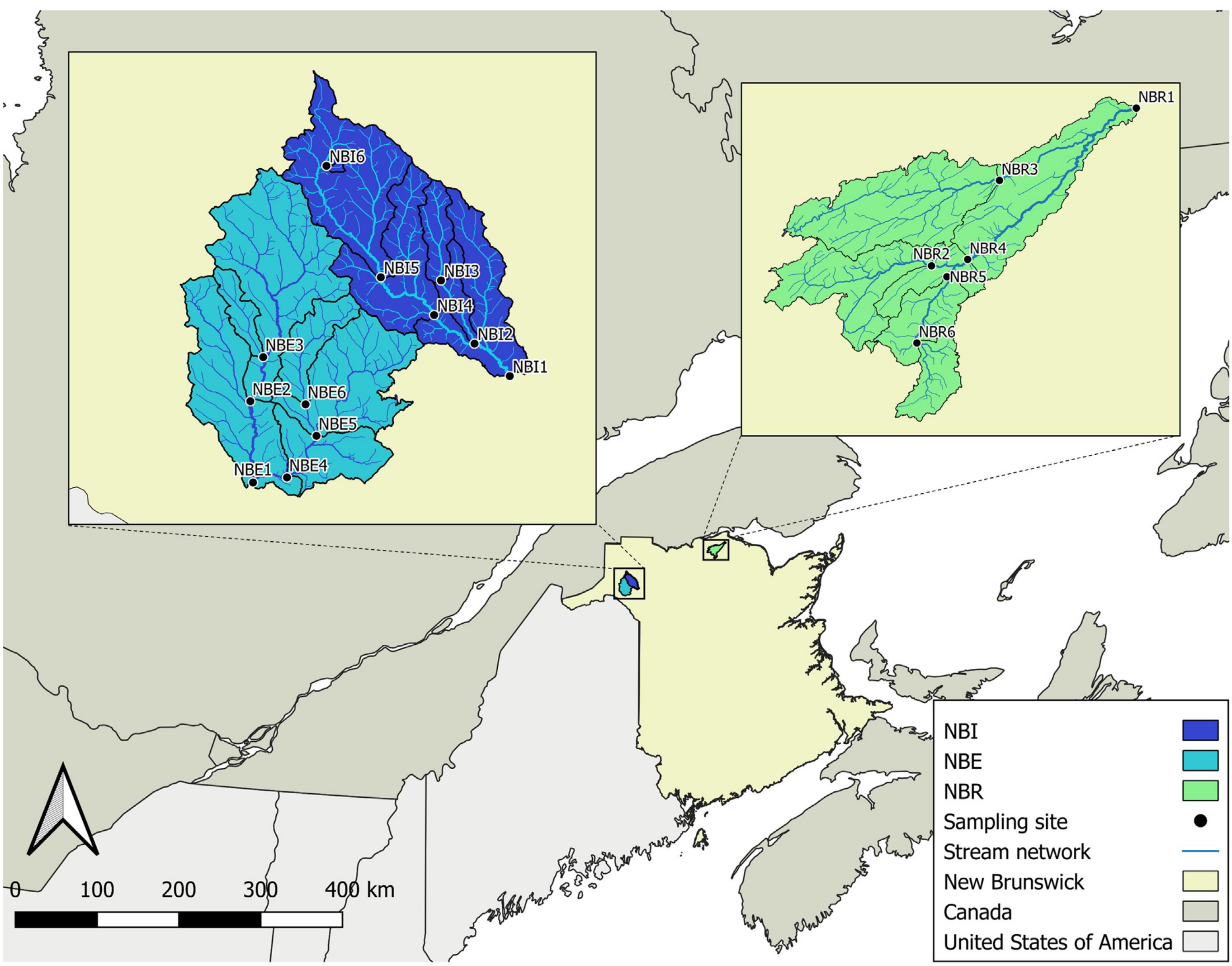

Fig. 2. Map showing the location of New Brunswick (Canada), the three study basins (NBE – extensively managed, NBI – intensively managed, NBR – reference) and the 18 stream sites and corresponding sub-catchments.

This study investigated whether the effects of forest management on streams accumulate downstream by sampling sites along the longitudinal gradient in three basins differing in forest management intensity in northern New Brunswick (Canada). Cumulative or dissipative effects were inferred when forest management-related differences among basins increased or decreased from upstream to downstream waters in the managed basins relative to the less managed basin, respectively (Fig. 1b). Because some effects of disturbance may propagate differently (MacDonald and Coe, 2007), and thus certain components of aquatic ecosystems may respond to disturbance and connectivity differently, we used a suite of abiotic indicators to ensure a comprehensive understanding of how forest management is influencing fluvial networks across multiple scales. The specific objectives of the study were to assess how: 1) stream indicators change from small streams to downstream waters within basins, 2) forest management intensity and other catchment characteristics are influencing stream indicators across various spatial scales, and, 3) longitudinal trends compare among basins with different management intensities to detect potential cumulative effects and to determine whether current management practices differ in effectiveness at protecting aquatic ecosystems across scales. We predicted that inorganic sediments, cation and DOC concentrations and water temperatures would increase longitudinally, that they would be greater in the managed basins relative to the less managed one, and that differences would increase longitudinally due to a greater downstream accumulation. Conversely, we predicted that the greater nutrient concentrations in the small streams of managed basins would be mitigated downstream due to a greater longitudinal decrease resulting from biological uptake and transformation.

2. Methods

2.1. Study area

This study was conducted in three basins each established in areas of differing forest management type in northern New Brunswick (NB, Canada) (Fig. 2). A sub-basin of the Restigouche River located in Black Brook forestry district (privately owned and operated by J.D. Irving) was selected to represent intensive forest management (NBI hereafter). This district is considered one of the most intensively managed forests in the country, with plantation regeneration and various stand improvement interventions implemented to maximize yield (Etheridge et al., 2005). A sub-basin of the Quisibis River was selected to represent a more extensive type of forest management (NBE); forests are left to regenerate naturally after harvesting, resulting in less intervention and longer rotation cycles. Finally, a sub-basin of the Charlo River was selected to represent minimal, or "reference", management (NBR). This basin is identified as a "designated watershed" by the Government of New Brunswick as it supplies municipal drinking water to the community, and therefore, forest management guidelines are stricter (e.g., wider riparian buffers, smaller cut blocks) (GNB, 2020). NBI and NBE are part of the Madawaska ecodistrict in the Central Uplands ecoregion in the northwestern part of the province. This is characterized by cool temperatures (1400–1600 annual degree-days above 5 °C), fairly abundant precipitation (475–525 mm May–September) and non-calcareous Ordovician–Devonian metasedimentary rocks (Zelazny, 2007). The vegetation originally consisted of a mixture of hardwood and coniferous tree species such as sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), white spruce (*Picea glauca*) and balsam fir (*Abies balsamea*), although commercial forestry has favoured the distribution of spruce. Given the intensity of forestry in the region, our minimally managed site (NBR) had to be located further away, in the Northern Uplands ecoregion (northeastern part of the province) on the junction of the Upsalquitch, Tetagouche and Tjigog ecodistricts. This ecoregion is considered slightly cooler (1300–1550 annual degree-days above 5 °C) and drier (400–500 mm May–September) than that of NBI and NBE and is composed mainly of Silurian–Devonian calcareous metasedimentary rocks with intrusions of volcanic rocks (Zelazny, 2007). The vegetation is similar to the Madawaska ecodistrict however, with a similar mixture of hardwood and coniferous tree species as is found in the Central Uplands.

Within each of the three basins (representing the three management types), six stream sites were selected to represent an upstream-downstream gradient (Fig. 2). Since the contributing catchment area increases along this gradient, drainage area was used to quantitatively capture the upstream-downstream direction. Note that some but not all six sites were located along the same flowpath because of site access issues (Fig. 2); however, we assumed that the same longitudinal processes were happening along different flowpaths within the same basin. The watershed of each site was delineated based on the 20-m provincial digital elevation model (DEM). Then, each sub-catchment was characterized (see Section 3.3), yielding 18 sub-catchments that ranged in drainage area (0.7–233.5 km^2), harvest intensity (0–23% and 0–24% of the catchment harvested in the 10 years prior to the 2017 and 2018 sampling, respectively), road density (1.30–3.58 km/km^2), and forest structure (6–16 m average height) and composition (38–89% deciduous cover) (Table 1).

Table 1
UTM coordinates (19T zone) and catchment characteristics of the 18 sampling sites (DTW – mean depth-to-water).

Stream-site	X	Y	Drainage area (km^2)	Total disturbance (%, 2009–18)	Clearcut (%, 2009–18)	Crossing density (#/km)	Road density (km/km^2)	Forest height (m)	Deciduous cover (%)	DTW (m)
NBE1	47.36078	−68.07194	233.5	14.1	5.4	0.45	2.41	13.2	63.9	22.9
NBE2	47.41159	−68.07556	85.3	17.8	4.4	0.56	2.69	10.6	71.7	27.1
NBE3	47.43935	−68.06444	9.2	0.0	0.0	0.08	3.58	16.0	78.4	27.1
NBE4	47.36435	−68.04194	93.2	13.8	7.7	0.34	2.17	14.2	56.6	18.6
NBE5	47.39061	−68.01389	68.0	16.6	8.6	0.31	2.31	13.8	57.7	18.7
NBE6	47.41004	−68.02500	18.1	20.7	10.1	0.48	2.73	14.5	76.2	22.1
NBI1	47.43016	−67.83639	163.0	24.3	2.6	0.78	2.43	6.5	68.8	25.2
NBI2	47.45257	−67.87028	20.6	22.3	2.0	0.47	2.13	7.7	71.0	23.5
NBI3	47.48940	−67.90139	11.8	21.7	2.6	0.61	1.91	6.9	80.7	21.9
NBI4	47.46766	−67.90750	102.5	22.5	1.3	0.92	2.49	6.5	71.5	26.1
NBI5	47.49055	−67.95722	62.0	21.4	1.1	0.83	2.33	6.4	73.1	25.4
NBI6	47.55868	−68.00972	0.7	6.4	0.0	0.00	1.30	6.1	89.0	22.9
NBR1	47.94969	−66.40167	167.5	7.3	4.1	0.35	1.99	13.9	49.4	17.8
NBR2	47.86021	−66.57194	33.2	5.5	4.1	0.36	1.95	15.1	41.5	16.3
NBR3	47.91020	−66.51417	51.0	11.5	3.6	0.37	2.14	13.0	52.3	11.9
NBR4	47.86387	−66.54222	73.2	6.8	5.8	0.36	2.00	15.0	46.1	17.5
NBR5	47.85406	−66.55833	28.5	7.8	6.8	0.38	2.04	14.8	47.8	16.4
NBR6	47.81680	−66.58472	12.5	7.2	7.2	0.17	1.70	13.8	38.4	13.0

2.2. Measurement of stream indicators

Sediment deposition was measured by deploying seven sediment traps (centrifuge tubes placed in bricks) on the stream bottom in depositional areas along the 100-m long sampling-reach for 71–74 days during August–October in 2017 and 2018. In the lab, fine (1.2–250 μm) organic and inorganic sediment content was measured following the protocol described in Erdozain et al. (2018).

Water temperature was continuously measured during the sampling season (June–October) with temperature and level data loggers, and monthly averages for daily maximum, minimum and mean temperatures were calculated.

Water samples were collected at the downstream end of each sampling reach in August, September and October of 2017–2018. Samples were kept refrigerated and in the dark until analyzed in the lab. Once in the lab, water chemistry samples were either preserved prior to analysis (cations/metals/total N and P) or analyzed within 24 h (pH/conductivity/alkalinity), 48 h (nutrients/carbon) or a week (SiO_2/SO_4/Cl) at the central Water Chemistry Laboratory at the Great Lakes Forestry Centre (GLFC; Sault Ste. Marie, ON, Canada) following standard methods (Hazlett et al., 2008). Water samples for dissolved organic matter (DOM) quality were filtered at 0.2 μm and characterized using Cary Eclipse (Varian Instruments, Walnut Creek, California, USA) and Cary 60 UV–Vis (Agilent Technologies, Santa Clara, California, USA) spectrophotometers in the Watershed Ecology Team Laboratory (WET lab) at the GLFC. Three-dimensional fluorescence scans were run at 5 nm excitation steps from 250 to 450 nm, and emissions were read at 2 nm steps from 300 to 600 nm. After correcting and adjusting the generated excitation-emission matrices, variables describing optical properties of DOM were calculated: HIX, an indicator of the humification degree of DOM (calculated following Zsolnay et al., 1999); SUVA, an indicator of DOM aromaticity (Weishaar et al., 2003); and the fluorescence index (FI), an indicator of DOM origin (terrestrial vs. microbial) (McKnight et al., 2001).

2.3. Explanatory catchment variables

Explanatory variables for the catchments were classified into three categories: forest management (harvesting and roads), landscape characteristics, and forest condition (structure and composition). Harvest variables were calculated from the GIS information on stands harvested each year, available from the province (NBE, NRB) and J.D. Irving (NBI). In each catchment, the area harvested each year by different methods was calculated and divided by total area to calculate the percentage of the catchment harvested. Harvesting method was either clearcut, in which ~>80% of the trees are removed, or partial, in which ~35–50% of the trees are removed. Total management disturbance was the sum of % clearcut, % partial harvest and % artificial regeneration. These yearly values were then summarized into variables of the cumulative percentage of the catchment harvested in the last 5 and 10 years prior to sampling (e.g., 2008–2017 and 2009–2018 for 10 years). Road variables were calculated from the road shapefiles obtained from GeoNB and included road crossings (number of times that a road crosses a stream upstream from each sampling site), road crossing density (road crossings divided by stream length), road length (sum of all road lengths in the catchment) and road density (road length divided by the area of the study catchment) (Table 1).

Several landscape features that could potentially affect stream ecosystems were quantified from the 20-m provincial DEM and stream shapefile using Whitebox GAT (Lindsay, 2016), and included catchment area, drainage density (stream length divided by catchment area), mean catchment slope, mean catchment elevation and catchment elevation range. To characterize catchment wetness, depth-to-water (DTW) values were calculated in ArcGIS as described by Murphy et al. (2011), and mean catchment DTW (Table 1) and % DTW < 0.1, 0.1–1, 1–20 and >20 m (not shown) were calculated.

Forest condition variables were derived from the provincial and J.D. Irving forest resource inventories. Forest structure was quantified by calculating the average height, crown closure, vertical stand structure and developmental stage. Forest composition was characterized by calculating the relative area covered by each tree species in the overstory (>2 m height) and understory (<2 m) layers; these data were summarized by running a non-metric multidimensional scaling analysis and calculating deciduous vs. coniferous cover.

2.4. Statistical analyses

Prior to exploring the relationships between indicators and explanatory variables, a subset of these variables was selected. The selection was based on Pearson's correlation analyses and/or principal components analyses (PCAs) within each stream indicator category (sediments, temperatures, water chemistry, DOM quality) and within each catchment variable category (forest management, landscape characteristics and forest condition). When variables were highly correlated, one variable was selected as representative. For example, mean, maximum and minimum July, August and September temperatures were strongly correlated, so only one variable (mean September temperature) was used in statistical analyses (see Table 2 for selected explanatory variables and associations with other variables). Box plots were constructed, and analysis of variance (ANOVA) with Tukey's post-hoc tests were performed for each stream indicator and catchment explanatory variable to test for among-basin differences.

Linear regression analyses were conducted to quantify and compare the strength of the relationship between a given stream indicator (mean value for indicators with replicates) and each explanatory variable. Because the relationship could be basin specific, basin type (intensive, extensive, minimal) was included in the models, and the interaction between explanatory variables and basin type was assessed. Models were built using data from the two sampling years; year was included as an explanatory variable and stream-site as a random variable to account for the repeated measures (*lme4* package; Bates et al., 2015). Type II ANOVAs (*car* package; Fox and Weisberg, 2019) were used to test the significance of the fixed effects in the mixed effects models, i.e., sampling year, basin type, the explanatory variable and the interaction term. Regression models and potential interactions were visualized by plotting the relationship between stream indicators and each explanatory variable for each basin separately. Additionally, simple linear

Table 2
Explanatory variables selected for regression analyses and other variables within the same category that were strongly correlated ($r > |0.80|$) with the selected one.

Category	Selected variable	Relationship to other variables
Forest management	Clearcut <10 years (%)	+ly: Clearcut <5 years
	Total disturbance <10 years (%)	+ly: Total disturbance <5 years, partial harvest <5 and 10 years
	Road density (km/km^2)	
	Crossing density (#/km)	
Landscape	Area (km^2)	+ly: road length, stream length, stream crossings, elevation range
	Slope (%)	+ly: mean depth to water (DTW), mean elevation −ly: % DTW 0.1–1 and 1–20 m
	DTW < 0.1 m (%)	
Forest condition	Forest height (m)	+ly: mean crown closure, mean # of vertical layers, % over-mature forest −ly: <10% and 10–30% crown closure, zero vertical layers
	Overstory deciduous cover (%)	+ly: total deciduous cover −ly: coniferous cover

regressions were run separately for each basin to quantify and compare the indicator-explanatory variable associations among forest management types; stream-site was also included as a random effect to account for repeated measures; the R^2 and *p*-value were recorded.

The plots and regression model results with the logarithm of drainage area as explanatory catchment variable were used to examine whether: 1) indicators showed longitudinal trends from small streams to downstream waters (e.g., sink or source function as shown in Fig. 1a), and 2) longitudinal trends varied among basins (i.e., significant drainage area × basin interaction). For significant interactions, cumulative or dissipative effects were inferred when forest management related differences among basins increased or decreased longitudinally, respectively, in NBI or NBE relative to NBR. All statistical analyses were performed in R 3.6.1 (R Core Team, 2019).

3. Results

3.1. Among-basin comparisons

The catchment conditions were significantly different among the three basins of different forest management type (Fig. 3). As expected, the intensively managed forest basin (NBI) had the highest and the minimally managed basin (NBR) the lowest percentage of total disturbance ($F_{2,15} = 6.5$, $p = 0.007$), respectively, within the previous 10 years (2009–2018) of this study, with the extensively managed basin (NBE) having intermediate percentages. Additionally, NBI had greater stream crossing density ($F_{2,15} = 2.6$, $p = 0.10$), slope ($F_{2,15} = 10.6$, $p = 0.001$) and deciduous cover ($F_{2,15} = 24.4$, $p < 0.001$) than the other two basins, but lower clearcut intensity ($F_{2,15} = 6.1$, $p = 0.01$) and forest height ($F_{2,15} = 76.3$, $p < 0.001$). NBE did not significantly differ from NBR in crossing density, clearcut intensity and forest height, but had the greatest road density ($F_{2,15} = 4.9$, $p = 0.02$). NBR had the greatest DTW < 0.1 m values ($F_{2,15} = 11.5$, $p = 0.001$), but the lowest deciduous cover values. There was also greater variability in disturbance conditions among sites in NBI and NBE compared to those in NBR (Fig. 3).

NBR had distinct stream water chemistry compared to the other basins, whereas NBE and NBI had greater overlap (water chemistry PCA, 63.4–71.1% of the variability captured depending on month; August 2018 shown in Fig. 4). NBR had higher base cation and anion influence and acid neutralizing capacity (indicated by greater conductivity, pH, alkalinity, and DIC, Ca, Mg, K, Cl, Na and SO_4 concentrations) than in NBI and NBE. The six sites in NBI had similar stream water chemistry (i.e., ordinated closely together) and they overlapped with two of the NBE sites, with the other four NBE sites having higher organic matter influence (indicated by higher DOC, Mn, Al, Fe, TN and TP concentrations) than the NBI sites. The first and second principal components organized the water chemistry parameters in 2–3 distinct groups, therefore one representative parameter was selected per group for modeling purposes. The first group (indicative of base cation and anion influence and acid neutralizing capacity) was represented by conductivity and included pH, alkalinity, DIC, Ca, Mg, Cl, Na and SO_4. The second group (indicative of organic matter influence) was represented by DOC and included Mn, Fe and Al (organics-associated metals). To capture the nutrient gradients, SRP and $NO_2 + NO_3$ were selected as representatives from the remaining variables.

NBE had significantly more inorganic and organic sediment accumulation in the traps, higher DOC concentrations and humification values (HIX), and lower nitrate concentrations and fluorescence index values than NBI and NBR (Fig. 5). NBR had the highest conductivity values and lowest SRP concentrations, whereas the highest DOM aromaticity (SUVA) values were measured at NBI.

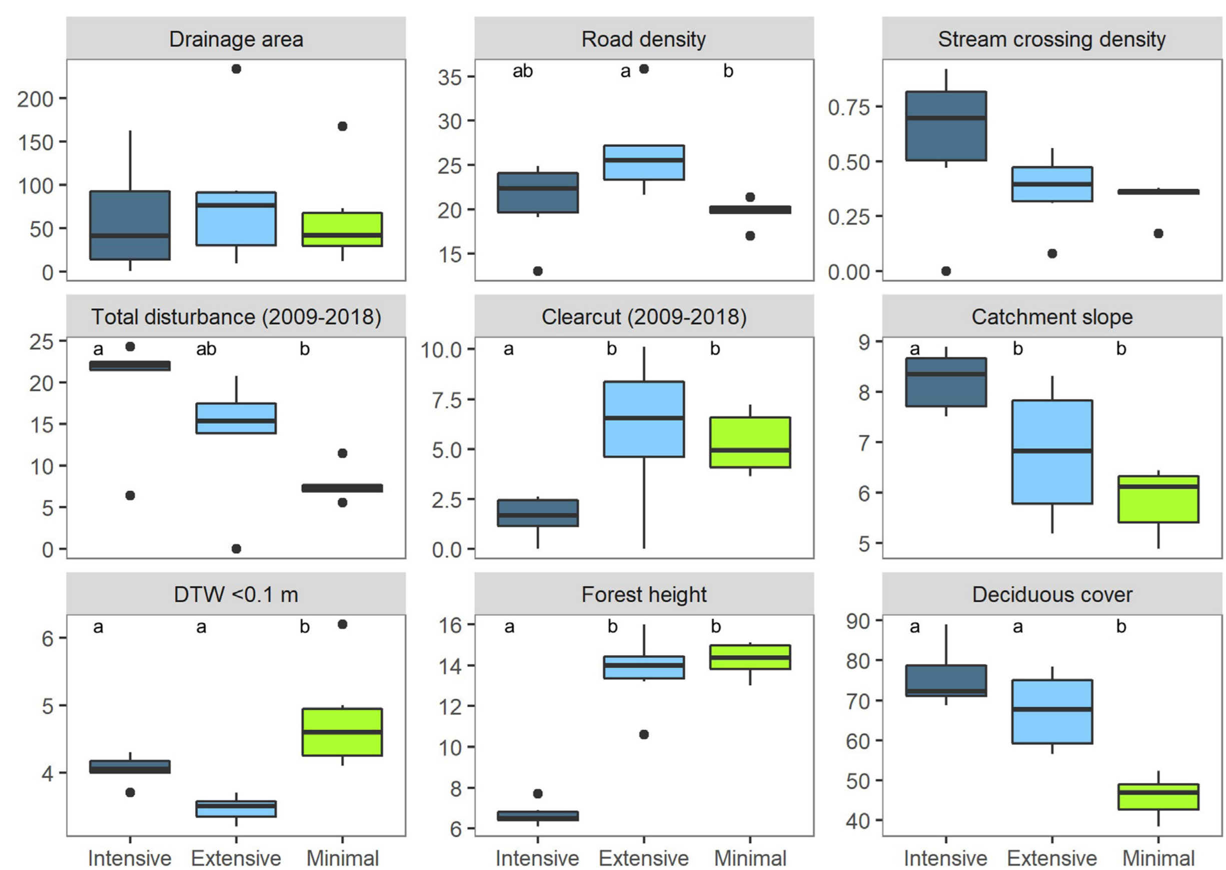

Fig. 3. Boxplots showing differences in catchment variables among the three basins ranging in forest management intensity. Letters represent significant ($p \leq 0.05$) differences among basins based on ANOVA and Tukey's post-hoc tests. Harvest variables represent 2009–2018 harvest data.

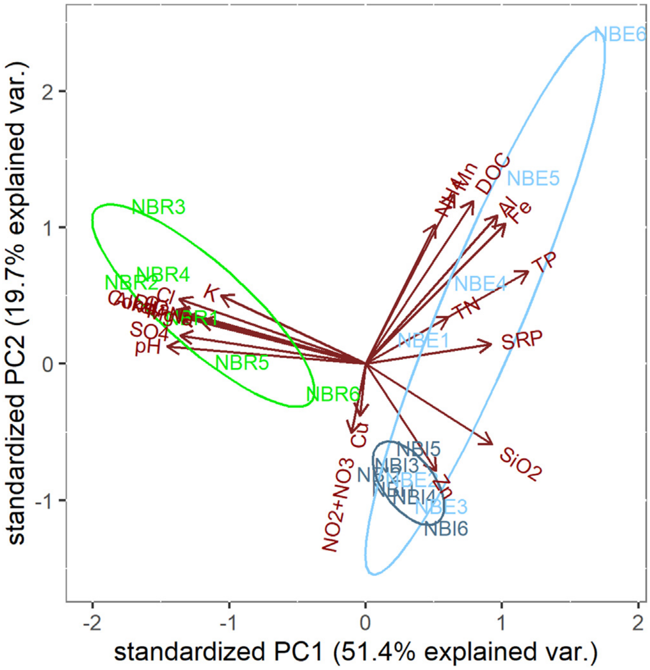

Fig. 4. Principal component analysis of water chemistry parameters (indicated by red arrows) from samples collected at 6 sites within three basins (intensive – dark blue, extensive – light blue and minimal – green) in August 2018. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Longitudinal trends within and among basins

Several abiotic indicators showed significant longitudinal trends from smaller to larger, downstream sites (Fig. 6). More specifically, inorganic sediments, the inorganic/organic ratios in traps and water temperatures significantly increased with drainage area, with the latter two also showing differences in slopes among basins (indicating an effect of forest management intensity on longitudinal trends). In contrast, SRP, nitrates and FI significantly decreased with drainage area; of these, SRP and FI did not show significant differences in slopes among basins whereas nitrates did.

Among-basin differences in the slopes of the longitudinal trends indicated accumulation or dissipation of effects due to forest management. The interaction between drainage area and basin was significant for organic sediments, the inorganic/organic ratios in traps, water temperatures and nitrates (Fig. 6). The increase in the inorganic/organic ratios in sediment traps with drainage area was significant in all three basins but steepest (greatest cumulation) at NBE followed by NBR (Fig. 7). There was evidence of longitudinal dissipation of organic sediments, with higher amounts in streams with smaller drainage areas than in those with larger drainage areas in NBE, but there was no such trend in the other basins. There was accumulation of inorganic sediments longitudinally, with significantly higher amounts in traps further downstream in NBI and NBE, but not in NBR. The increase in water temperatures with drainage area was greatest and significant in NBR followed by NBI, whereas NBE showed no significant longitudinal change and little differences in temperatures among sites. The longitudinal decrease in nitrates was greatest and significant in NBR followed by NBI, i.e., smaller streams had higher values than larger rivers, but there was no such trend in NBE. The opposite was observed for SRP; the longitudinal decrease was greatest and significant in NBE and NBI, whereas NBR had consistently lower concentrations across all sites.

Note that the smallest stream in NBI had a considerably smaller drainage area (0.66 km^2) than the smallest streams in NBE (9.19 km^2) and NBR (12.53 km^2). To make sure that the wider range in drainage areas in NBI was not having a disproportionate influence on the above-reported results, analyses excluding NBI6 were also run and results are shown in SI Figs. S1 and S2. Most general longitudinal trends were detected even when NBI6 was excluded; therefore, we are confident about the trends that include this stream. Differences in the results with and without this site will be mentioned in the discussion.

3.3. The effect of forest management intensity and other catchment characteristics

In addition to the effects of longitudinal position (i.e., drainage area), other catchment characteristics influenced the differences in sediment indicators among sites. Sediment deposition was positively related to several measures of forest management intensity (Fig. 8). Fine inorganic sediments and the inorganic/organic ratios significantly increased with total disturbance and stream crossing density, but the increase in the ratios with crossing density was steeper for NBE than NBI (significant interaction). These relationships were also strongest for NBI and NBE and non-significant for NBR. Organic sediments significantly increased as forest height increased. In addition, within NBI, organic sediments increased with clearcut and decreased with slope.

Water temperature was also significantly and positively related to crossing density and total disturbance, but no interactions among basins were found (Fig. 9). In contrast, the slopes between water temperature and road density, clearcut or deciduous cover showed significant interactions among the three basins. For example, the relationship between water temperature and clearcut was significantly positive and steepest for NBI, positive but less steep for NBE and, interestingly, significantly negative for NBR. Overall, the strongest relationships between water temperature and forest management variables were found for NBI; for NBE, this endpoint was not significantly related to any catchment variable.

Some effects of management intensity and catchment characteristics were also found for water chemistry variables. Conductivity was significantly and negatively related to total disturbance and had significant interactions with stream crossings or road density (positive relationships only for NBR) (Fig. 10). At NBI, conductivity was strongly and negatively related to slope and DTW < 0.1 m and positively related to forest height. DOC concentrations were significantly and positively related to clearcut and total disturbance, and negatively to slope and deciduous cover, with the clearcut model explaining most of the variance (Fig. 10). The basin $\times$ clearcut and basin $\times$ road density interactions for this variable were significant; DOC significantly increased with clearcut at NBE, but there were non-significant increases and decreases at NBI and NBR, respectively. SRP significantly decreased with crossing density and total disturbance and increased with deciduous cover (Fig. 10). Within basins, however, significant relationships were only detected at NBI and with crossing density and deciduous cover. Nitrates were significantly related to crossing density and DTW < 0.1 m, and the basin interaction was significant for crossing and road density, clearcut and deciduous cover. Relationships tended to be strongest at NBR followed by NBI.

Measures of DOM quality also showed some effects of catchment characteristics and forest management. HIX significantly increased with clearcut and total disturbance, and decreased with slope and deciduous cover, with the clearcut model explaining most of the variance (Fig. 11). The basin $\times$ road density interaction was significant; HIX values decreased with road density at NBE and NBR but increased at NBI. FI significantly decreased (i.e., more terrestrial origin of DOM) with crossing density and total disturbance (Fig. 11). These relationships were strongest at NBE (where the fluorescence index was also negatively related to clearcut) followed by NBI, but this was not observed at NBR. SUVA significantly increased with crossing density, total disturbance and deciduous cover (Fig. 11). However, within basins, significant relationships between SUVA and catchment variables were only observed at NBI, and these were strongly influenced by the most upstream of the six sites.

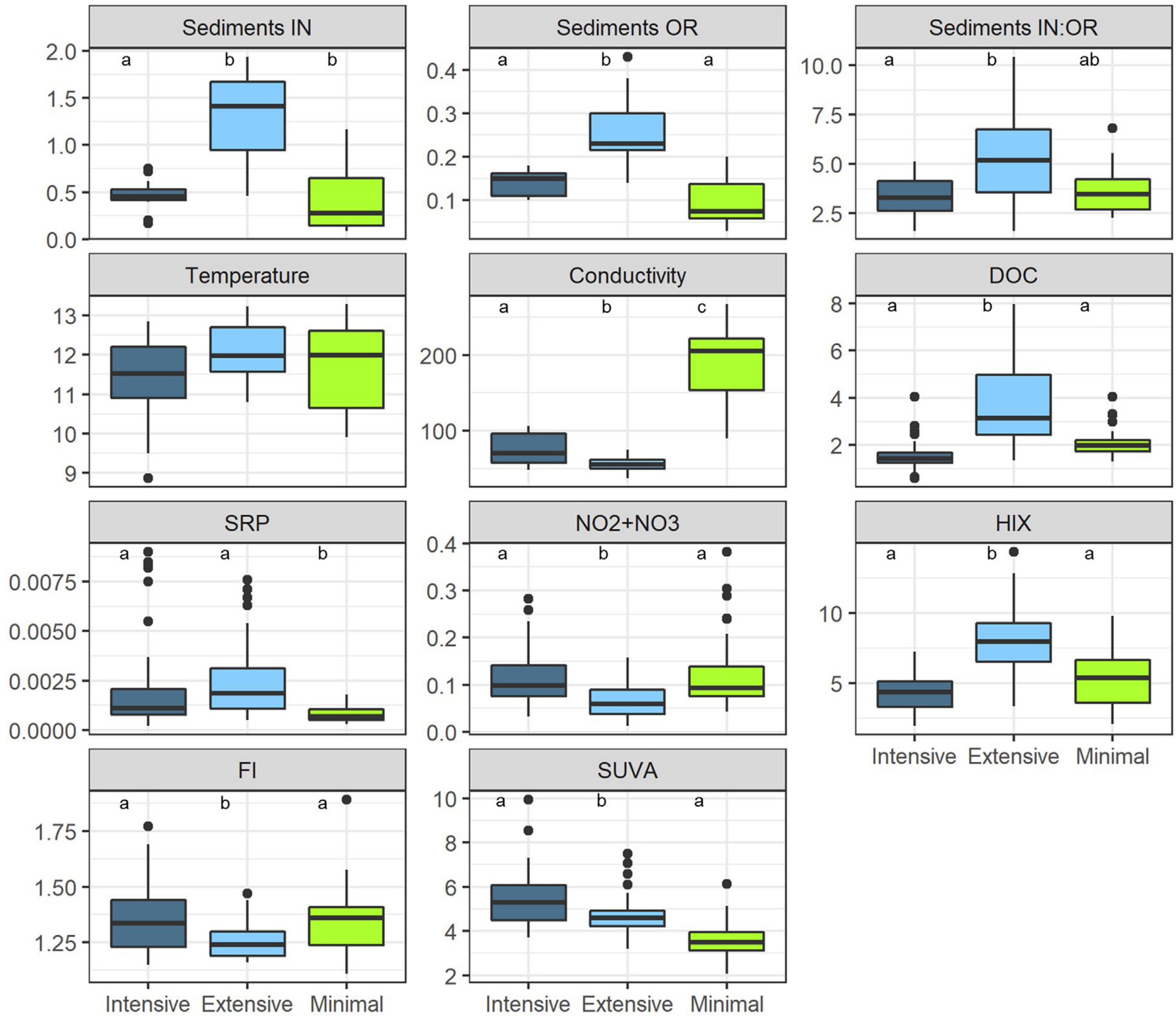

Fig. 5. Boxplots showing differences in abiotic stream indicators among the three basins ranging in forest management intensity. Letters represent significant ($p \leq 0.05$) differences among basins based on ANOVA and Tukey's post-hoc tests.

	p Drainage area	*p* Drainage area x Basin	R^2_m	R^2_c
Inorganic sediments	**6.2; 0.01**	3.6; 0.16	0.66	0.78
Organic sediments	1.2; 0.26	**11; 0.004**	0.73	0.79
Inorganic / Organic	**23.5; <0.001**	**12.1; 0.002**	0.64	0.71
Temperature	**29.1; <0.001**	**6.7; 0.03**	0.71	0.90
Conductivity	0.8; 0.35	5.4; 0.07	0.78	0.99
DOC	0.7; 0.38	0.4; 0.82	0.39	0.75
SRP	**19.1; <0.001**	2.7; 0.26	0.57	0.91
NO_2+NO_3	**6.8; 0.009**	**7.3; 0.03**	0.45	0.75
DOM humification	0.2; 0.63	4.2; 0.12	0.46	0.65
Fluorescence index	**4.1; 0.04**	0.2; 0.91	0.17	0.35
DOM aromaticity	**5.1; 0.02**	1.8; 0.41	0.60	0.66

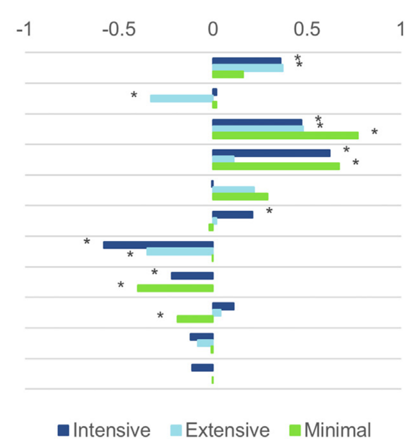

Fig. 6. Results of linear regressions between stream indicators (rows) and the logarithm of drainage area in three basins (6 sites per basin) over two years. The table shows Wald chisquare statistics and *p*-values from mixed model ANOVAs testing the significance of drainage area (DF = 1) and the drainage area × basin interaction (DF = 2) in the following model: Stream variable = log(Drainage area) × Basin + Year + (1 | Site); marginal and conditional R^2 values are shown and $p \leq 0.05$ bolded. The plot shows the variance explained by the logarithm of drainage area within each basin based on the model: Stream variable = log(Drainage area) + (1 | Site); the colors of the bars represent the basin, the length of the bars match the marginal R^2s, the sign of the values or direction of the bars represent the sign of the coefficient (+ or − relationship), and the asterisk indicates $p \leq 0.05$.

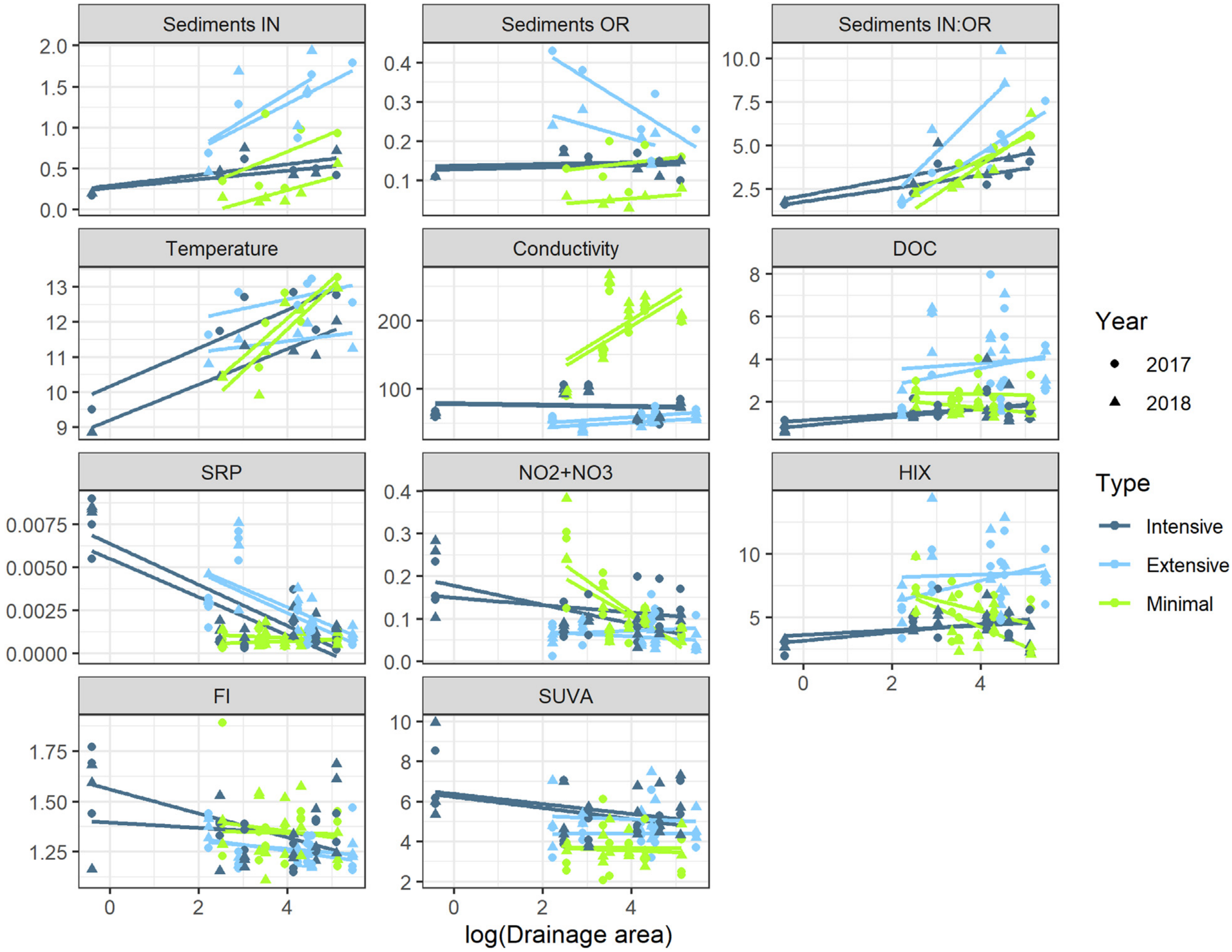

Fig. 7. Linear relationship between abiotic stream indicators (y-axis) and the logarithm of drainage area (x-axis) in three basins differing in forest management intensity (dark blue – intensive, light blue – extensive, and green – minimal) in 2017 and 2018 (circles and triangles, respectively). Six sites per basin were sampled.

4. Discussion

4.1. Longitudinal trends

Across all basins, inorganic sediments and the inorganic/organic ratios increased longitudinally, but this was not observed for organic sediments. Streams can be a sink for sediments by trapping them via deposition in floodplains and riparian wetlands (Kleiss, 1996; Noe and Hupp, 2009) or retaining them behind large wood jams (Elosegi et al., 2017). However, in the current study those processes were not always strong enough to counteract the fundamentally cumulative nature of rivers (MacDonald and Coe, 2007; Leibowitz et al., 2018). The lack of a spatial relationship for organic sediments may be because the sinks (e.g., consumption and transformation by heterotrophs, riparian flooding) were balanced by the sources (e.g., longitudinal cumulative source function, leaf breakdown) (Fritz et al., 2018).

Of the other measures of water quality assessed herein, reactive phosphorus, nitrates/nitrites, temperature and FI (but not conductivity, DOC, HIX, SUVA) showed significant longitudinal patterns. Nutrient concentrations decreased longitudinally, indicating strong biological demands and/or biochemical transformations (Mulholland et al., 2008; McGuire et al., 2014) that resulted in an overall sink function from upstream to downstream (Leibowitz et al., 2018). For DOC, longitudinal trends have been detected with high-density stream sampling over short distances (<1500 m) (Zimmer et al., 2013; McGuire et al., 2014) but over the larger scales of the current study, multiple controls at landscape (e.g., forest disturbance, forest type, soil, topography), riparian (discontinuous DOC contributions through discrete riparian input points) and in-stream reach (e.g., photo-oxidation, outgassing to the atmosphere, microbial processing) scales (e.g., Dick et al., 2015; Demars, 2019; Lupon et al., 2019) likely interacted to reduce longitudinal trends. The decrease in FI suggested a more terrestrial origin of DOM in downstream waters (McKnight et al., 2001). For parameters related to mineral weathering, such as conductivity, McGuire et al. (2014) showed broad-scale dissimilarity related to changes in bedrock as well as dissimilarity among short unconnected distances. The former would explain the higher base cation and anion influence and acid neutralizing capacity in NBR (calcareous metasedimentary rocks, Zelazny, 2007) than in NBE and NBI (non-calcareous metasedimentary rocks, Zelazny, 2007) and the latter why we did not see clear longitudinal patterns as not all sites within a basin were flow-connected. Finally, the increase in temperatures downstream is common as headwaters tend to be cooler as a result of snowmelt, greater relative riparian shading and/or steeper channels (Fullerton et al., 2015). However, the slopes of these longitudinal trends differed among the three basins and these differences are discussed in more detail below (Section 4.3).

4.2. The effect of forest management intensity and other catchment characteristics

Our analyses indicated that catchment factors other than drainage area also affected the abiotic variables measured herein, and of these,

Inorganic sediments	EV	Basin	Year	INT	R^2_m
Drainage area	**6.2; 0.01**	**34.9; <0.001**	1.2; 0.27	3.6; 0.16	0.66
Crossing density	**3.9; 0.05**	**40.8; <0.001**	1.5; 0.22	4.6; 0.10	0.65
Road density	1.9; 0.17	**31.4; <0.001**	1.5; 0.22	**6.5; 0.04**	0.65
Clearcut	2.1; 0.14	**22.2; <0.001**	0.9; 0.34	2.5; 0.29	0.61
Tot. disturbance	**9.0; 0.003**	**44.5; <0.001**	**4.0; 0.04**	5.2; 0.07	0.69
Slope	1.1; 0.28	**29.6; <0.001**	1.5; 0.21	2.8; 0.24	0.59
DTW<0.1m	0.0; 0.87	**12.6; 0.002**	1.5; 0.22	0.4; 0.81	0.52
Height	0.5; 0.47	**25.9; <0.001**	1.5; 0.22	3.2; 0.20	0.59
Deciduous cover	2.4; 0.12	**29.3; <0.001**	1.5; 0.22	0.2; 0.88	0.57
Organic sediments					
Drainage area	1.2; 0.26	**52.2; <0.001**	**17.2; <0.001**	**11.0; 0.004**	0.73
Crossing density	0.4; 0.53	**34.5; <0.001**	**15.9; <0.001**	4.4; 0.11	0.66
Road density	1.6; 0.21	**12.7; 0.002**	**15.8; <0.001**	1.5; 0.48	0.63
Clearcut	0.0; 0.98	**24.0; <0.001**	**13.7; <0.001**	0.1; 0.96	0.58
Tot. disturbance	1.1; 0.29	**38.9; <0.001**	**13.3; <0.001**	5.5; 0.06	0.68
Slope	0.1; 0.78	**27.2; <0.001**	**15.5; <0.001**	1.3; 0.53	0.60
DTW<0.1m	1.6; 0.21	**11.6; 0.003**	**15.5; <0.001**	5.0; 0.08	0.68
Height	**30.2; <0.001**	**108.0; <0.001**	**17.2; <0.001**	0.8; 0.69	0.80
Deciduous cover	0.3; 0.57	**22.7; <0.001**	**15.7; <0.001**	1.8; 0.39	0.62
Inorganic : Organic ratio					
Drainage area	**23.5; <0.001**	**9.9; 0.007**	**4.8; 0.03**	**12.1; 0.002**	0.64
Crossing density	**6.4; 0.01**	**12.9; 0.001**	**4.0; 0.05**	**6.1; 0.05**	0.48
Road density	0.7; 0.41	**6.8; 0.03**	**4.0; 0.04**	**7.6; 0.02**	0.42
Clearcut	0.1; 0.76	3.4; 0.18	**5.0; 0.02**	2.6; 0.27	0.29
Tot. disturbance	**9.9; 0.002**	**13.2; 0.002**	1.7; 0.19	2.1; 0.35	0.46
Slope	0.3; 0.57	4.3; 0.11	**4.0; 0.04**	1.0; 0.62	0.24
DTW<0.1m	0.2; 0.63	4.3; 0.12	**4.0; 0.04**	1.5; 0.46	0.26
Height	**6.7; 0.01**	**14; <0.001**	**3.9; 0.05**	4.6; 0.10	0.47
Deciduous cover	2.0; 0.15	**7.6; 0.02**	**3.9; 0.05**	2.6; 0.27	0.34

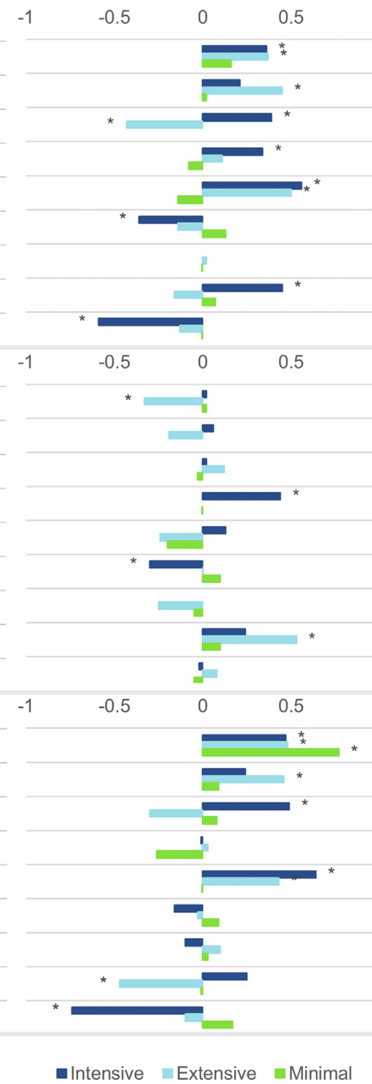

Fig. 8. Results of linear regressions between three sediment indicators (inorganic and organic sediment content and ratios in traps) and catchment explanatory variables (EV) in three basins (6 sites per basin) over two years. The table shows Wald chisquare statistics and *p*-values from mixed model ANOVAs testing the significance of each parameter in the following model: Stream variable (e.g. sediments) = Catchment variable (DF = 1) × Basin (DF = 2) + Year (DF = 1) + (1 | Site) [INT = interaction term, DF = 2]; marginal and conditional R^2 values are shown and $p \le 0.05$ bolded. The plots show the variance explained by each catchment variable within each basin based on the model: Stream variable (e.g. sediments) = Catchment variable + (1 | Site); the colors of the bars represent the basin, the length of the bars match the marginal R^2s, the sign of the values or direction of the bars represent the sign of the coefficient (+ or − relationship), and the asterisk indicates $p \le 0.05$.

Water temperature	EV	Basin	Year	INT	R^2_m
Drainage area	**29.1; <0.001**	1.2; 0.56	**43.2; <0.001**	**6.7; 0.03**	0.71
Crossing density	**8.3; 0.004**	**7.2; 0.03**	**42.6; <0.001**	0.7; 0.71	0.46
Road density	2.3; 0.13	1.2; 0.54	**42.4; <0.001**	**12.5; 0.002**	0.55
Clearcut	1.6; 0.21	0.8; 0.67	**21.2; <0.001**	**18.0; <0.001**	0.56
Tot. disturbance	**4.1; 0.04**	5.7; 0.06	**40.2; <0.001**	3.8; 0.15	0.43
Slope	0.9; 0.35	1.1; 0.57	**42.0; <0.001**	0.8; 0.65	0.25
DTW<0.1m	2.8; 0.09	4.2; 0.12	**42.2; <0.001**	0.2; 0.89	0.30
Height	0.4; 0.51	1.5; 0.48	**42.4; <0.001**	2.3; 0.32	0.29
Deciduous cover	3.2; 0.07	5.1; 0.08	**42.5; <0.001**	**15.5; <0.001**	0.59

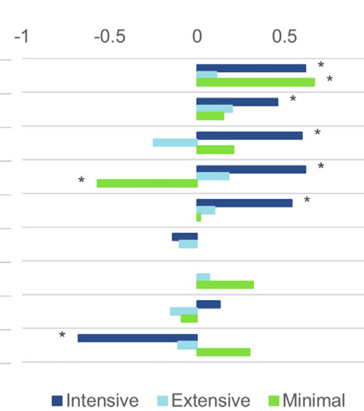

Fig. 9. Results of linear regressions between mean September water temperatures and catchment explanatory variables in three basins (6 sites per basin) over two years. See Fig. 8 for details.

Conductivity	EV	Basin	Year	Month	INT	R^2_m
Drainage area	0.8; 0.35	**60.6; <0.000**	0.0; 0.91	2.2; 0.33	5.4; 0.07	0.78
Crossing density	0.2; 0.66	**80.8; <0.001**	0.0; 0.91	2.2; 0.33	**12.8; 0.002**	0.84
Road density	0.1; 0.77	**49.8; <0.001**	0.0; 0.91	2.2; 0.33	**6.3; 0.04**	0.79
Clearcut	0.3; 0.58	**40.2; <0.001**	0.0; 0.94	2.3; 0.32	2.2; 0.33	0.70
Tot. disturbance	**16.7; <0.001**	**28.3; <0.001**	**3.7; 0.05**	2.6; 0.26	1.0; 0.60	0.7
Slope	0.0; 0.89	**35.0; <0.001**	0.0; 0.91	2.2; 0.33	2.9; 0.23	0.74
DTW<0.1m	2.7; 0.10	**15.8; <0.001**	0.0; 0.91	2.2; 0.33	2.2; 0.33	0.77
Height	0.5; 0.48	**39.6; <0.001**	0.0; 0.91	2.2; 0.33	1.9; 0.38	0.74
Deciduous cover	0.1; 0.80	**17.9; <0.001**	0.0; 0.91	2.2; 0.33	1.6; 0.45	0.72
DOC						
Drainage area	0.7; 0.38	**13.3; 0.001**	0.9; 0.33	**11.6; 0.003**	0.4; 0.82	0.39
Crossing density	0.9; 0.33	**16.2; <0.001**	0.9; 0.34	**11.6; 0.003**	0.3; 0.85	0.40
Road density	3.3; 0.07	**29.2; <0.001**	0.9; 0.34	**11.6; 0.003**	**9.3; 0.009**	0.55
Clearcut	**29.2; <0.001**	**20.8; <0.001**	0.3; 0.61	**11.1; 0.004**	**7.7; 0.02**	0.65
Tot. disturbance	**9.3; 0.002**	**28.3; <0.001**	**3.9; 0.05**	**12.2; 0.002**	1.5; 0.47	0.51
Slope	**21.5; <0.001**	**42.5; <0.001**	0.9; 0.34	**11.6; 0.003**	4.1; 0.13	0.62
DTW<0.1m	0.6; 0.43	**13.8; 0.001**	0.9; 0.34	**11.6; 0.003**	0.9; 0.65	0.40
Height	0.1; 0.80	**9.0; 0.01**	0.9; 0.34	**11.6; 0.003**	0.7; 0.69	0.39
Deciduous cover	**4.9; 0.03**	**25.8; <0.001**	0.9; 0.34	**11.6; 0.003**	1.9; 0.37	0.50
SRP						
Drainage area	**19.1; <0.001**	**6.7; 0.03**	**9.4; 0.002**	**19.6; <0.001**	2.7; 0.26	0.57
Crossing density	**8.8; 0.003**	**9.0; 0.01**	**9.4; 0.002**	**19.6; <0.001**	1.7; 0.43	0.43
Road density	2.8; 0.09	**7.5; 0.02**	**9.4; 0.002**	**19.6; <0.001**	**9.7; 0.008**	0.47
Clearcut	1.4; 0.24	3.3; 0.19	**9.3; 0.002**	**19.9; <0.001**	1.6; 0.44	0.23
Tot. disturbance	**10.1; 0.001**	**12.5; 0.002**	**17.7; <0.001**	**19.3; <0.001**	2.0; 0.36	0.40
Slope	0.9; 0.33	1.6; 0.45	**9.4; 0.002**	**19.6; <0.001**	3.6; 0.16	0.30
DTW<0.1m	0.1; 0.71	0.7; 0.69	**9.4; 0.002**	**19.6; <0.001**	1.7; 0.42	0.21
Height	0.4; 0.51	3.6; 0.16	**9.4; 0.002**	**19.6; <0.001**	**5.8; 0.05**	0.34
Deciduous cover	**8.8; 0.003**	3.3; 0.19	**9.4; 0.002**	**19.6; <0.001**	5.6; 0.06	0.49
$NO_2 + NO_3$						
Drainage area	**6.8; 0.009**	**5.9; 0.05**	0.5; 0.46	**20.7; <0.001**	**7.3; 0.03**	0.45
Crossing density	**5.7; 0.02**	**12.8; 0.002**	0.5; 0.46	**20.7; <0.001**	**16.6; <0.001**	0.51
Road density	2.9; 0.09	1.1; 0.58	0.5; 0.46	**20.7; <0.001**	**10.2; 0.006**	0.44
Clearcut	2.1; 0.15	**10.7; 0.005**	1.7; 0.19	**21.2; <0.001**	**17.6; <0.001**	0.48
Tot. disturbance	1.0; 0.30	4.7; 0.10	0.1; 0.74	**20.9; <0.001**	2.8; 0.24	0.27
Slope	0.1; 0.70	4.1; 0.13	0.5; 0.46	**20.7; <0.001**	1.5; 0.46	0.23
DTW<0.1m	**5.0; 0.02**	**10.0; 0.007**	0.5; 0.46	**20.7; <0.001**	0.1; 0.95	0.32
Height	0.7; 0.38	3.8; 0.15	0.5; 0.46	**20.7; <0.001**	0.4; 0.81	0.21
Deciduous cover	0.1; 0.77	5.1; 0.08	0.5; 0.46	**20.7; <0.001**	**6.6; 0.04**	0.35

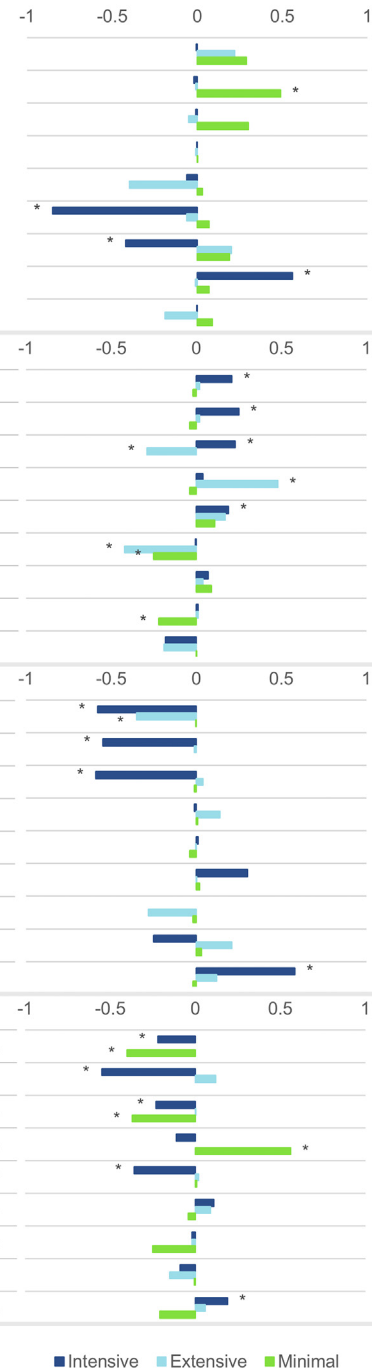

Fig. 10. Results of linear regressions between water chemistry parameters and catchment explanatory variables in three basins (6 sites per basin) over two years. See Fig. 8 for details.

forest management related variables had the strongest influence. More specifically, total disturbance was related to the highest number of indicators (9 out of 11, all except organic sediments and nitrates), followed by crossing density (7 out of 11). Most of the relationships we observed support the literature on the responses of small streams to forest management. However, our study included larger downstream sites and suggests that the effects of forest management are not solely confined to small streams, as observed by others (Martel et al., 2007).

In the current study, forest management variables predicted each abiotic indicator except organic sediments. The increases in inorganic sediments caused by forest harvesting and roads, such as those observed herein, have been well documented (Croke and Hairsine, 2006; Webster et al., 2015; Al-chokhachy et al., 2016; Erdozain et al., 2018). DOC concentrations increased with harvest but, interestingly, were more strongly predicted by proportion of clearcut than total harvest, suggesting that the complete removal of trees had a greater effect than partial harvest on DOC concentrations (Kreutzweiser et al., 2008; Erdozain et al., 2018). The quality of DOM was also related to clearcut (HIX only), total disturbance (HIX, FI) and crossing density (FI), indicating that DOM became more humic (higher HIX) and of a greater terrestrial origin (lower FI; McKnight et al., 2001) with increasing management intensity. Most of these effects suggest a greater transport of suspended and dissolved terrestrial materials to fluvial systems with more forest management, likely due to increased water delivery after harvesting exacerbated by roads, soil disturbance by machinery, reduced soil stability and enhanced biogeochemical processes in soils

HIX	EV	Basin	Year	Month	INT	R^2_m
Drainage area	0.2; 0.63	**26.4; <0.001**	0.3; 0.60	3.8; 0.15	4.2; 0.12	0.46
Crossing density	0.8; 0.38	**30.3; <0.001**	0.2; 0.61	3.7; 0.16	4.6; 0.10	0.48
Road density	3.3; 0.07	**41.5; <0.001**	0.2; 0.62	3.5; 0.17	**10.0; 0.007**	0.54
Clearcut	**23.6; <0.001**	**26.1; <0.001**	0.1; 0.76	3.1; 0.21	0.5; 0.79	0.56
Tot. disturbance	**7.1; 0.007**	**34.7; <0.001**	1.3; 0.25	3.4; 0.18	1.1; 0.57	0.49
Slope	**12.1; <0.001**	**38.8; <0.001**	0.2; 0.63	3.5; 0.17	0.2; 0.90	0.53
DTW<0.1m	0.3; 0.60	**15.1; <0.001**	0.2; 0.62	3.7; 0.16	0.9; 0.62	0.42
Height	0.1; 0.80	**14.3; <0.001**	0.2; 0.63	3.7; 0.16	1.1; 0.56	0.42
Deciduous cover	**6.0; 0.01**	**37.3; <0.001**	0.2; 0.62	3.6; 0.17	0.4; 0.81	0.49
Fluorescence index						
Drainage area	**4.1; 0.04**	4.2; 0.12	0.5; 0.47	0.5; 0.77	0.2; 0.91	0.17
Crossing density	**7.8; 0.005**	12.3; 0.002	0.5; 0.47	0.5; 0.76	0.1; 0.93	0.21
Road density	0.3; 0.59	3.7; 0.16	0.5; 0.48	0.5; 0.77	8.2; 0.02	0.21
Clearcut	3.3; 0.07	3.5; 0.17	1.6; 0.20	0.4; 0.82	5.7; 0.06	0.21
Tot. disturbance	**8.3; 0.004**	13.8; 0.001	0.0; 0.81	0.5; 0.79	1.1; 0.56	0.22
Slope	1.1; 0.30	5.0; 0.08	0.6; 0.44	0.5; 0.77	0.7; 0.70	0.13
DTW<0.1m	0.5; 0.47	4.7; 0.10	0.6; 0.44	0.5; 0.76	0.2; 0.92	0.11
Height	0.0; 0.95	4.0; 0.13	0.6; 0.45	0.6; 0.74	3.5; 0.17	0.16
Deciduous cover	3.1; 0.08	9.3; 0.009	0.5; 0.48	0.5; 0.77	2.2; 0.33	0.18
SUVA						
Drainage area	**5.1; 0.02**	**45.1; <0.001**	**4.2; 0.04**	**67.0; <0.001**	1.8; 0.41	0.60
Crossing density	**4.9; 0.03**	**59.2; <0.001**	**4.2; 0.04**	**66.9; <0.000**	3.9; 0.14	0.61
Road density	2.9; 0.09	**61.6; <0.001**	**4.2; 0.04**	**67.0; <0.001**	**6.8; 0.03**	0.62
Clearcut	1.3; 0.25	**47.8; <0.001**	2.1; 0.14	**67.1; <0.001**	**11.0; 0.004**	0.62
Tot. disturbance	**6.5; 0.01**	**72.3; <0.001**	**5.5; 0.02**	**67.4; <0.001**	**13.4; 0.001**	0.64
Slope	1.6; 0.20	**13.3; 0.001**	**4.1; 0.04**	**67.0; <0.001**	3.7; 0.16	0.59
DTW<0.1m	0.0; 0.86	**25.3; <0.001**	**4.0; 0.04**	**66.8; <0.001**	0.0; 0.99	0.55
Height	2.2; 0.13	**17.8; <0.001**	**4.1; 0.04**	**66.9; <0.001**	**8.7; 0.01**	0.62
Deciduous cover	**5.2; 0.02**	4.1; 0.13	**4.3; 0.04**	**66.9; <0.001**	4.9; 0.08	0.62

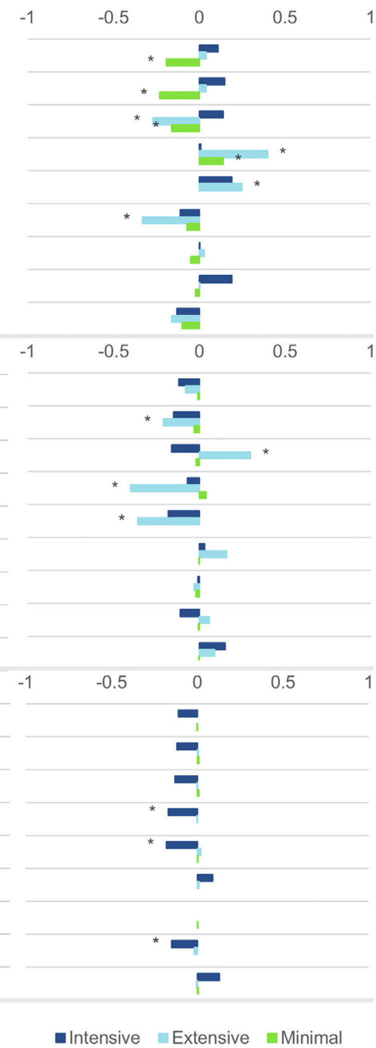

Fig. 11. Results of linear regressions between DOM quality parameters (DOM humification or HIX, fluorescence index, and DOM aromaticity or SUVA) and catchment explanatory variables in three basins (6 sites per basin) over two years. See Fig. 8 for details.

(Kreutzweiser et al., 2008; Webster et al., 2015). In contrast, the decrease in SRP and nitrates/nitrites with crossing density and total disturbance could be attributed to rapid uptake by post-harvest vegetation regeneration or increased microbial immobilization (Growns and Davis, 1991, Trayler and Davis, 1998, Whitson et al., 2005). However, these relationships were strongly influenced by the smallest NBI site, and once excluded, nutrients showed a positive relationship with clearcut intensity. Finally, despite maintaining buffer zones in these streams, we found warmer water temperatures at sites with greater total disturbance or crossing density that is likely related to the warming of groundwater in areas with upland clearing and bare roads (Moore et al., 2005; Witt et al., 2016).

Although forest disturbance-related variables had the greatest effects, we also found effects of catchment gradient and wetness and forest composition and structure on these abiotic indicators. For example, catchment slope was negatively related to DOC and HIX, and could be due to steeper catchments having a greater flushing potential (i.e., shorter water residence times in contact with organic layers) and fewer flat areas known for creating conditions optimal for the accumulation and processing of high-quality organic matter (Webster et al., 2008; Mengistu et al., 2014). Catchments with a greater proportion of deciduous stands exported less DOC and less humic DOM but more SRP, as observed elsewhere (Thieme et al., 2019).

4.3. Cumulative effects

Based on the comparisons of upstream to downstream trends among basins for the abiotic variables, three main patterns were observed: 1) differences between minimal and intensively- or extensively-managed basins became greater longitudinally, indicating cumulative effects; 2) differences disappeared or decreased longitudinally, indicating dissipative effects; or 3) there was no longitudinal change in the differences among basins (Fig. 1). The first was observed for inorganic sediments, the second for organic sediments, water temperature, SRP and nitrates and the third for DOC quantity and quality, suggesting that not all measures of water quality had the same longitudinal response to the effects of forest management.

Cumulative effects of forest management were observed in the current study for inorganic sediments and the inorganic/organic ratios as their increase with drainage area was greatest for the extensive (NBE) basin. Although the intensive basin (NBI) had the highest total disturbance and stream crossings of all three basins, the cumulative increase in inorganic sediments only for NBE can be explained because: 1) NBE had more clearcut than NBI, and the transport of sediments from clearcut stands is greater than from partially harvested ones (Croke and Hairsine, 2006); 2) NBI is more intensively managed (Etheridge et al., 2005) and, therefore, has more effective BMPs for preventing sediments from reaching streams; and 3) the steeper channel slopes at NBI may have a greater capacity to transport the sediments away from the study reaches. Regardless of the cause, the greater downstream accumulation of inorganic sediments for NBE could have detrimental biological implications (Jones et al., 2012).

Dissipative effects were observed herein for organic sediments, water temperature, SRP and nitrates. Small streams at NBE and NBI had warmer temperatures than the same-sized streams at NBR, which is a well-documented effect of forest management on streams (Moore et al., 2005; Erdozain et al., 2018). Yet, downstream water temperatures were comparable across basins likely due to differences in the longitudinal thermal patterns among basins: NBR showed the steepest linear warming pattern, whereas NBI and NBE had less steep linear and uniform thermal patterns, respectively (Fullerton et al., 2015). The potential processes preventing cumulative temperature effects herein could be dilution with cooler groundwater or tributary inputs (Dugdale et al., 2013; Ploum et al., 2018) and/or steeper slopes of the intensive and extensive channels that decrease the time for water to heat up en route (Fullerton et al., 2015). However, the lower temperature ranges observed at the extensive and, to a lesser extent, intensive basins could be problematic as small streams act as cold-water refuges for multiple aquatic organisms (e.g., Dugdale et al., 2015; Ebersole et al., 2015). Small streams had more organic sediments at NBE than in other basins, and more SRP and less nitrates/nitrites at NBE and NBI than at NBR, but these differences weakened or disappeared downstream due to organic sediments and SRP decreasing longitudinally at NBE and nitrates/nitrites at NBR. This matches trends observed in forested streams where the time and distance necessary for nutrient uptake is very short (Feller, 2005). It is interesting that NBE and NBI had more SRP but less nitrates/nitrites than NBR in small streams. Phosphorus is delivered to streams on soil particles, and, thus, greater soil disturbance at NBE and NBI would result in greater delivery, whereas wetter soils (Fig. 3) and riparian forests dominated by alder (Erdozain personal observation) at NBR could facilitate atmospheric N fixation and potentially explain the higher nitrate/nitrite concentrations (Feller, 2005). In short, in-stream processes likely reduced the downstream transport of these materials and dissipated cumulative effects, but these sink functions will likely have biological implications (e.g., increased algal biomass).

In the current study, the weak spatial changes in DOC quantity and quality suggested that these measures mostly matched the third spatial pattern described above, but some evidence of cumulative effects was also observed. NBI maintained the highest SUVA values and NBE the highest DOC concentrations and HIX values from small streams to larger rivers. The latter two variables were most strongly and positively related to % clearcut herein and in other studies (see review by Webster et al., 2015), which would explain why NBE - the basin with greatest % clearcut - had the highest values for DOC and HIX. Although we did not detect spatial patterns across all basins, within NBR there was a slight sink function for DOC and HIX which resulted in a larger downstream gap between NBE and NBR and hints at potential cumulative effects. Additionally, the longitudinal decrease in FI (see Section 4.1), especially for NBE and NBI, suggested that forest management led to downstream DOM with greater terrestrial origin (see Section 4.2). Increased delivery of terrestrial materials related to forest management has been linked to increased allochthony in small stream food webs (Erdozain et al., 2019), which has implications as terrestrial food sources are of lower nutritional quality than aquatic ones (Brett et al., 2017); therefore, it is important to assess whether the downstream accumulation of terrestrial materials herein is incorporated into food webs (Erdozain et al., submitted). DOM related indicators were highly variable over time and their dependence on hydroclimatic conditions could explain why we could not detect clearer forest management-related cumulative effects; therefore, future studies at higher temporal and spatial resolutions are recommended (McGuire et al., 2014).

Finally, relationships between indicators and forest management variables across the three basins (described in Section 3.2) were more often detected for NBI and NBE than for NBR. More specifically, the greatest number of indicators were predicted by total disturbance, road density or drainage area at NBI (6 of 11), by total disturbance for NBE (5 of 11) and by drainage area at NBR (4 of 11). This suggests that longitudinal hydrologic transport exerts greater control over these indicators than catchment conditions in watersheds with less disturbance.

Although the presence/absence of cumulative effects has been inferred using NBR as a reference, it is important to note that this basin also underwent forest management, although to a lesser extent. Two of the sites were downstream of stream crossings and the minimal basin had higher clearcut intensities than the intensive basin, which is a harvest practice with greater impacts on streams than partial harvest (Croke and Hairsine, 2006; Kreutzweiser et al., 2008; Yeung et al., 2017). In addition, the six NBR sites had similar crossing density, road density and total disturbance values, which could have limited our detection of management effects across basins. Finally, only one basin per management type and six sites per basin were sampled, meaning the study had low spatial resolution and no replication. Therefore, our understanding of the cumulative effects from forest management would benefit from comparisons to a less disturbed basin, as well as from spatially extensive studies that compliment our intensive work and that include more sites along the river continuum and more basins per management type.

5. Conclusions and recommendations

We detected some downstream cumulative effects of forestry by comparing the longitudinal trends of abiotic indicators in three basins ranging in forest management intensities. Differences in inorganic sediments, the inorganic/organic ratios and, to a lesser extent, DOC concentrations and humification between the extensively managed and the two other basins increased upstream to downstream. Differences in temperatures, organic sediments and nutrients, on the other hand, diminished longitudinally, showing that sink functions of streams were stabilizing potential cumulative effects. However, we detected most of the same forest management impacts that are usually reported in small streams (e.g., greater delivery of sediments and DOC, warmer temperatures) when larger downstream sites were included in the models. This is interesting because it shows that effects were not just limited to small streams with an intimate connection to the surrounding land but also extended downstream. In addition, the impacts of forest management on streams were greatest at the extensive than intensive basin, suggesting that greater overall intensity of forestry does not necessarily translate into greater environmental impacts when more sustainable practices are applied (e.g., partial vs. clearcut harvest). Modified management practices within the extensive basin may reduce the cumulative downstream effects related to the increased delivery of terrestrial materials to streams.

CRediT authorship contribution statement

Maitane Erdozain: Formal analysis, Investigation, Writing - original draft, Visualization. **Karen A. Kidd:** Conceptualization, Investigation, Writing - review & editing, Funding acquisition. **Erik J.S. Emilson:** Investigation, Writing - review & editing. **Scott S. Capell:** Investigation. **David P. Kreutzweiser:** Conceptualization, Funding acquisition. **Michelle A. Gray:** Conceptualization, Investigation, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.141968.

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