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Research papers

Long-term effects of forest harvesting on summer low flow deficits in the Coast Range of Oregon

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ABSTRACT

We examined long-term changes in daily streamflow associated with forestry practices over a 60-year period (1959–2017) in the Alsea Watershed Study, Oregon Coast Range, Pacific Northwest, USA. We quantified the response of daily streamflow to (1) harvest of mature/old forest in 1966, (2) 43- to 53-yr and 48- to 58-yr-old industrial plantation forests in 2006–2009, and (3) logging of the plantations using contemporary forest practices, including retention of a riparian buffer, in 2010 and 2014. Daily streamflow from a 40- to 53-yr-old Douglas-fir plantation was 25% lower on average, and 50% lower during the summer (June 15 to Sept 15 of 2006 to 2009), relative to the reference watershed containing mature/old forest. Low flow deficits persisted over six or more months of each year. Surprisingly, contemporary forest practices (i.e., clearcutting of the plantation with riparian buffers in 2009 and 2014) had only a minor effect on streamflow deficits. Two years after logging in 2014, summer streamflow deficits were similar to those observed prior to harvest (under 40- to 53-yr-old plantations). High evapotranspiration from rapidly regenerating vegetation, including planted Douglas-fir, and from the residual plantation forest in the riparian buffer appeared to explain the persistence of streamflow deficits after logging of nearly 100% of the forest plantation. Results of this study indicated that 40- to 50-yr rotations of Douglas-fir plantations can produce persistent, large summer low flow deficits. While the clearcutting of these plantations, with retention of riparian buffers, increased daily streamflow slightly, flows did not return to pre-first entry conditions. Further work is needed to examine how intensively managed plantation forests along with expected warmer, drier conditions in the future may influence summer low streamflow and aquatic ecosystems.

1. Introduction

Climate change, natural disturbances, and human activities have raised concerns about both the short- and long-term effects on water supplies originating from forests (Flörke et al., 2018; Hellema et al., 2018; Vörösmarty et al., 2010). Much of the concern is, in part, the result of dramatic increases in disturbances in forests—a trend projected to continue in many regions globally (Hansen et al., 2013; Nolan et al., 2018). Widespread forest disturbance may alter forested headwater watersheds, whose structure, composition, and health influence water supplies for aquatic ecosystems and for downstream uses (Brown et al., 2008; Creed et al., 2014; Ellison et al., 2012; McDonnell et al., 2018).

Long-term data from experimental watershed studies provide key information about effects of environmental change on water supply (Cosgrove and Loucks, 2015; Laudon et al., 2017; Tetzlaff et al., 2017). Over the last century, paired watershed studies in North America (e.g., Wagon Wheel Gap Project, H.J. Andrews Experimental Forest, Caspar Creek Experimental Forest, Hubbard Brook Ecosystem Study, Coweeta Hydrologic Laboratory, and the Alsea Watershed Study) have revealed effects of forest practices on streamflow over the short-term (Bates and Henry, 1928; Hewlett and Helvey, 1970; Jones and Grant, 1996; Likens et al., 1970; Stednick, 2008; Ziemer, 1998) and the long-term (Jones et al., 2012; Turner et al., 2003).

Much of the paired watershed research has focused on forest management effects on peak flows and annual water yields (Bosch and

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Hewlett, 1982; Grant et al., 2008; Stednick, 1996) and factors influencing variability in these responses (Brown et al., 2005; Moore and Wondzell, 2005). The recent global expansion of industrial plantation forestry (e.g., Hansen et al., 2013) has raised concerns about the long-term hydrologic effects of forest plantations (Ferraz et al., 2013; Scott, 2005). Experimental watershed studies have provided evidence that low flows may increase in the first decade following harvest of mature or old-growth forest (with and without riparian buffers), but low flows may decline in subsequent decades, as vegetation regenerates (Jones and Post, 2004; Moore and Wondzell, 2005; Rothacher, 1970; Surfleet and Skaugset, 2013).

However, few studies have sufficient data to reveal long-term effects of forest harvest and plantations on summer low flows. In a recent analysis of 60 years of daily streamflow data from eight paired watersheds in the Cascade Range, Oregon, USA, summer streamflow fell below pre-treatment levels within 15 years after old-growth forest harvest (Perry and Jones, 2017). Additionally, these low flow deficits persisted and intensified for ~50 years as the Douglas-fir (*Pseudotsuga menziesii*) plantations became established (Perry and Jones, 2017). Long-term declines in low flows associated with forest harvesting and plantations raise concerns about aquatic ecosystem health and water supply, especially in dry years (Leppi et al., 2012; Luce and Holden, 2009).

Despite these observations, several important questions about the magnitude and longevity of the effects of forest harvesting and industrial plantation forestry remain unanswered. Thus, research from long-term watershed studies is needed to compare streamflow response to harvest of mature and old-growth forest with the streamflow response to contemporary forestry practices, which involve clearcutting of 30- to 50-year plantations with riparian buffers. Harvest of plantations may temporarily increase summer low flows (Surfleet and Skaugset, 2013), but it is unclear whether contemporary forest practices can restore low flows to levels produced by mature and old-growth forest. The Alsea Watershed Study in the Oregon Coast Range provided a unique opportunity to address these uncertainties. The study included an initial phase of harvest of mature/old forest (1959–1973) (Harr and Krygier, 1972), growth of Douglas-fir plantations, a second harvest in 2009 of 43- to 53-yr-old and in 2014 of 48- to 58-yr-old plantations using contemporary forestry practices, including a riparian buffer, and a final post phase (2015–2017) with riparian trees 51- to 61-yr-old. We addressed the following questions:

1) How did harvest of 43- to 58-yr-old Douglas-fir plantations with riparian buffers influence streamflow compared to harvest of unmanaged mature/old forest in the Oregon Coast Range, Pacific Northwest, USA?
2) What processes explain these responses in the Alsea compared to other long-term watershed experiments in the region?

2. Study site

The Alsea Watershed Study (44.5 °N, 123.9 °W) was established in September 1958 (Fig. 1). The study area is located in the Siuslaw National Forest in the central Oregon Coast Range, draining highly-dissected terrain with short, steep, soil-mantled hillslopes underlain by the Tyee Formation, a rhythmically Eocene interbedded sandstone and mudstones deposit (Snavely et al., 1964). In general, the soil textures of these watersheds are loams and gravelly loams on the hillslopes and valley bottoms and clay loams on the ridges.

The region has a Mediterranean climate with dry summers and wet winters. The mean annual precipitation (MAP) (1981–2010) of the study region is 2192 mm (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 Feb 2004). The majority (75%) of precipitation occurs from October to April in long-duration, low-to-moderate intensity frontal storms (Harr, 1976). Snowfall rarely accumulates, so snowmelt is not a factor in the water balance (Hale and McDonnell, 2016). Precipitation and air temperature data were collected at the study watersheds for only part of the study period (1959–2017). The MAP at a nearby NOAA Station (No. 350145) did not differ significantly between the historic pre-treatment period (1959–1965) and the post first entry period (1967–1973) or between the pre-second entry period (2006–2009) and Phase I (2010–2014) or Phase II (2015–2017) of the second entry period (Supplementary Material A, Table S1). In addition, monthly precipitation at the NOAA station was stationary over the study period (1959–2017) (Supplementary Material Table S5). Nevertheless, the spring and summer of 2015 and 2017 were very dry (below the 15th percentile) compared to 2006 through 2014 (Supplementary Material, Fig. S1).

Mean annual temperature (MAT) was 10.8 °C for the period 1959–2017 (estimated from PRISM (Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 Feb 2004). The MAT was not significantly different between pre (1959–1965) and post (1967–1973) first entry or between the pre-entry (2006–2009) and Phase I (2010–2014) of the second harvest. However, temperature was statistically higher during the Phase II (2015–2017) compared to the 2006–2014 period (Supplementary Material A, Table S1). Temperature was cooler than average for Phase I (2010–2014): four out the five years were below the 20th percentile and two years were below the 10th percentile (Supplementary Material, Table S1). The temperature was very warm (above the 85th percentile) during six months of 2015 (October, December to March, and July) and during four months of 2016 (October, February, April, and May) (Supplementary Material, Fig. S1).

The Alsea Watershed Study is located within the *Tsuga heterophylla* vegetation zone (Franklin and Dyrness, 1988). The forest canopy is dominated by conifer species (Douglas-fir [*Pseudotsuga menziesii*] and western hemlock [*Tsuga heterophylla*]). Deciduous hardwood species (red alder [*Alnus rubra*] and big-leaf maple [*Acer macrophyllum*]) also are common (Franklin and Dyrness, 1988; Harrington et al., 1994). Understory species are dominated by salmonberry (*Rubus spectabilis*), vine maple (*Acer circinatum Pursh*), salal (*Gaultheria shallon Pursh*), and sword fern (*Polystichum munitum* (Kaulf.) C. Presl).

3. Watershed and treatment descriptions

3.1. Flynn Creek

The reference watershed, Flynn Creek (210 ha), is located on U.S. Forest Service land and is undisturbed by human activities (Fig. 1). Flynn Creek was designated a U.S. Forest Service Research Natural Area in 1975. Mean elevation is 272 m and the mean watershed slope gradient is 25°. The gravel bed stream has a gradient of 0.025 m/m (Moring, 1975) and summer mean wetted width of 1.3 m (Bladon et al., 2016). Canopy closure, as assessed with a spherical densiometer along the stream channel, was 91–92% between 2006 and 2012. Vegetation consists of two tree height cohorts (Fig. 1, Table 1): one at 32 m, corresponding to an estimated 60–70% cover of red alder and big-leaf maple, and another at 54 m, corresponding to an estimated 30–40% cover of Douglas-fir regenerated after fire in the mid to late 1800s (Hall and Stednick, 2008; Harris, 1977; Harris and Williams, 1971; Williams, 1964).

3.2. Deer Creek

Deer Creek (311 ha) is mostly on U.S. Forest Service land and was historically used to examine the impact of road building and extensive forest management on water quality (Harr et al., 1975). The mean elevation is 304 m and the mean gradient is 27°. The gravel bed stream has a gradient of 0.018 m/m and summer mean wetted width of 1.8 m (Moring, 1975). Roads were constructed in 1965 (Harr et al., 1975) and three 25-ha patch clearcuts were harvested between May and November 1966, using high-lead cable yarding with a riparian buffer

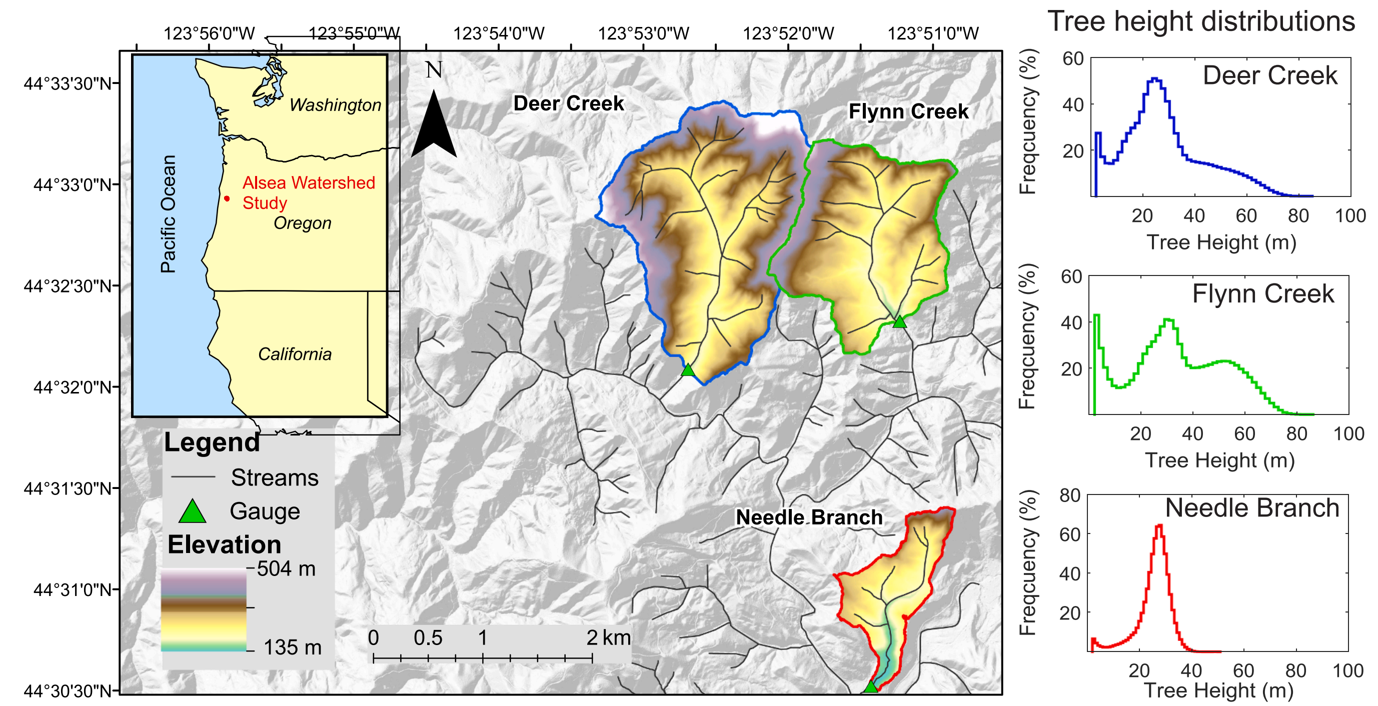

Fig. 1. Location and elevation of the Alsea Watershed Study and 2009 LiDAR derived tree height distribution in the three experimental watersheds of Deer Creek, Flynn Creek, and Needle Branch. Lidar acquisition occurred after the 2009 harvest in Needle Branch. Tree heights were obtained from the unharvested (lower) portion of the watershed.

along all streams (Fig. 2, Table A). Cutover units were broadcast burned and hand-planted with Douglas-fir, followed by herbicide treatments to control competing vegetation. Between 1978 and 1988 the USDA Forest Service (USFS) intermittently clear-cut harvested and thinned three small units totaling 44 ha (Table 1, Fig. 2). The USFS also thinned 59 ha in three management units in Deer Creek around 2006. This thinning was not a part of the study and details on the exact area and basal area removal/retention are not currently known. These thinning operations may have affected streamflow to some extent, but given the small spatial extent it is unlikely they affected the overall findings of our analysis for Deer Creek.

In 1959, vegetation consisted of 60–64% conifer forest dominated by post-fire Douglas-fir (50–70 and 70–110 years old) and 36–40% cover of 40 to 60-year-old deciduous hardwoods (Hall and Stednick, 2008; Harris, 1977; Harris and Williams, 1971). As of 1992, vegetation cover was 36% hardwoods, 33% pre-harvest conifers, and 31% regenerated conifer (Belt, 1997), producing a multi-modal distribution of tree heights in 2009 LiDAR data with a mode of 24 m (Fig. 1).

3.3. Needle Branch

Needle Branch (75 ha) is located on private industrial forest land and has served as the treatment watershed to examine historical (1960s) and contemporary (2000s) intensive harvesting practices. The mean elevation is 225 m and the mean gradient is 24°. The gravel bed stream has a gradient of 0.014 m/m (Moring, 1975) and a mean summer channel width of 1.1 m (Bladon et al., 2016). Canopy closure along the stream channel was 96% in 2006–2008 and 89% in 2010–2012. Roads were constructed in 1965 (Harr et al., 1975) and the watershed was 82% clearcut in 1966, with a combination of high-lead cable and tractor yarding. There was no riparian buffer, trees were yarded across the stream, and large wood and logging debris were cleared from the channel after clearcutting. The site was broadcast-burned, hand-planted with Douglas-fir, and treated with herbicide (Table 1). In 1956, 13 ha (17% of the drainage area) in the headwaters of Needle Branch were clear-cut (Hall and Stednick, 2008). Therefore, 100% of the watershed area was clear-cut between 1956 and 1966. Hence, the pre-treatment relationship between Needle Branch and Flynn Creek (1959–1966) reflects, in part, the conversion of 17% of Needle Branch from old forest to young plantation in 1956. At the time of the second harvest entry (2009), plantations in Needle Branch were aged 43 to 53 years. Pre-commercial thinning occurred in 1981 (Stednick and Kern, 1992). During the second (contemporary) harvest entry, the upper sub-watershed (34.9 ha) was clearcut harvested in 2009, and a lower section (36.8 ha) was clearcut in 2014 for a total clearcut of 96% of the drainage area (Fig. 2). Both clearcuts were completed using cable and tractor equipment. All trees in the cutover area were removed, including along three small, non-fish-bearing tributaries, but a ~15 m riparian management area was retained on each side of the fish-bearing portion of the stream in accordance with the Oregon Forest Practices Act and Rules (ODF, 1994). The riparian management area contained a minimum of ~ 3.7 m^2 conifer basal area per 300 m of stream length and four to five wildlife leave trees per hectare, as recommended by the Oregon Forest Practices Act (Adams and Storm, 2011). Aerial spraying of herbicide (a mixture of Accord1 XRT II [glyphosate], Chopper1 Gen II [imazapyr], and Sulfomet1 Extra [SMM and MSM]) occurred in August 2010 (Louch et al., 2017). Recent studies examined effects of these treatments on water temperature (Bladon et al., 2016), suspended sediment (Hatten et al., 2018), and fish (Bateman et al., 2018).

In 1959, vegetation consisted of 80–85% conifer forest dominated by post-fire Douglas-fir (70–110 years old) with some western red cedar (*Thuja plicata*) (30–50 years old) (Hall and Stednick, 2008; Harris and Williams, 1971; Williams, 1964). In 1992, 26 years after the initial harvest, vegetation was ~ 80% conifer and ~ 20% hardwood (Belt, 1997). At the time of the contemporary harvest (2009), vegetation was even-aged 43-yr-old Douglas-fir in 82% of the watershed and 53-yr-old Douglas-fir in 17% of the watershed with red alder occupying a significant portion of the riparian corridors. Mean tree height in the watershed in 2009 was 28 m (Fig. 1).

Table 1
Characteristics of study watersheds.

Watershed	Area (ha)	Mean Slope (degrees)	Elevation (m)	Natural vegetation	Streamflow record, missing days, instrumentation	Treatment, dates	Logging method
Flynn Creek (reference)	210	25	160–444	30–40% Douglas-fir (90–100, 130–170 yrs); 60–70% deciduous (alder, maple)	1959–1973 (47 days); 2006–2017 (214 days); broad-crested concrete weir	none	
Deer Creek	311	27	169–504	1959: 60–64% Douglas-fir (50–110 yrs), 36–40% deciduous; 1992: 64% Douglas-fir (including 31% 26-yr plantation), 36% deciduous,	1959–1973 (43 days); 2006–2017 (672 days); broad-crested concrete weir	1965: Roads; 1966: 25% clearcut in three 25-ha patches with riparian buffer, broadcast burning, manual planting, herbicide; 1978–1988: three clearcuts/thins (44 ha)	High-lead cable yarded
Needle Branch	75	24	135–373	1959: 80–85% Douglas-fir (70–110 yrs), western red cedar (30–50 yrs) and 15–20% Alder; 1992: 80% 26-yr Douglas-fir plantation, 20% deciduous; 2009–2014: 44-yr Douglas-fir plantation	1959–1973 (65 days); 2006–2017 (112 days); broad-crested concrete weir	1956: 13 ha in the headwaters were logged (Hall and Stednick, 2008); 1965: Roads; 1966: 82% clearcut, no riparian buffer, stream wood removal, broadcast burning, manual planting, herbicide; 1981: pre-commercial thin; 2009: upper 34.9 ha clearcut; 2014: lower 36.8 ha clearcut, 15-m riparian buffer. A 3.3-ha block in southwest extent of the watershed was not harvested due to different ownership.	High-lead cable yarded, some tractor yarding

4. Methods

4.1. Discharge record

Streamflow data were collected continuously during two periods. In the historical period, 1959 to 1973 (15 water years) data were tabulated at ~2-hour intervals, including seven years each of pre- and post-harvest data. In the contemporary period, 2006 to 2017 (12 water years), data were collected at 10-minute intervals, including three to eight years of pre-harvest data (Table 1, Fig. 3).

The watersheds were instrumented in 1958 with compound broad-crested concrete weirs located at the watershed outlets of Flynn Creek, Needle Branch, and Deer Creek (Harris, 1977b). Streamflow was monitored by the USGS from 1959 to 1973 by the Watershed Research Cooperative from 2006 to 2017 (Hatten et al., 2018). For the contemporary record (2006 to 2017), rating curves were developed based 40 to 55 stage-discharge data points collected for each watershed (Hatten et al., 2018). The historic record was practically complete, with less than 1% missing data, but there were 3–15% missing data in the contemporary record (Table 1, Fig. 3).

4.2. Daily average streamflow

Effects of forest harvest were calculated following methods in Jones and Post (2004) and Perry and Jones (2017). The difference (R) in mean daily flow (Q) normalized by drainage area between treated (Q_T) and reference (Q_R) watersheds was calculated for each day between 1959 and 1973 and between 2006 and 2017:

$$R = ln\left(\frac{Q_T}{Q_R}\right) \tag{1}$$

Q_R corresponded to the mean daily flow in Flynn Creek, while Q_T was the mean daily flow from either Needle Branch or Deer Creek. An $R = 0$ represented no difference in Q between a treatment and the reference, while values > 0 or < 0 represented increases or decreases in discharge relative to the reference.

Mean daily differences in daily flows between treated and reference watersheds ($\bar{R_d}$) were calculated for each day (d) and compared for various combinations of five pre- and post- treatment periods (Table 2). Each comparison was expressed as a percent difference for a given day (Δ_d):

$$\Delta_d = 100[e^{(R_{d,\bar{post}} - R_{d,\bar{pre}})} - 1] \tag{2}$$

Values of Δ_d were smoothed using a 15-day window (Perry and Jones, 2017). The five time periods were: 1959–1965 (before first entry), 1966–1973 (after first entry), 2006–2009 (before second entry), 2010–2014 (after second entry Phase I), and 2015–2017 (after second entry Phase II) (Table 2). Multiple comparisons were made among the various "pre" vs. "post" time periods (Table 2, Fig. 4). For Needle Branch (harvested) vs. Flynn Creek (reference), values of$\bar{R_d}$ before first entry ("pre") were compared to the following "post" periods: (a) after first entry, (b) before second entry Phase I, (c) after second entry Phase I, and (d) after second entry Phase II (Table 2, first four rows, column 2, solid arrows Fig. 4). In addition, for Needle Branch (treated) vs. Flynn Creek (reference), values of $\bar{R_d}$ were compared before the second entry ("pre") to the following "post" periods (a) after second entry Phase I and (b) after second entry Phase II (Table 2, rows 3 and 4, column 3, Fig. 4 dashed arrows). For Deer Creek (harvested) vs. Flynn Creek (reference), values of $\bar{R_d}$ before first entry were compared to (a) after first entry and (b) 40–51 years after the first entry (Table 2, rows 5 and 6, column 2, Fig. 4 solid arrows). There was no second harvest entry in Deer Creek as a part of this study design.

Annual water yields were compared between the treated and reference watersheds for various time periods to (1) determine whether annual water yields in the second entry pre-harvest period (2006–2009)

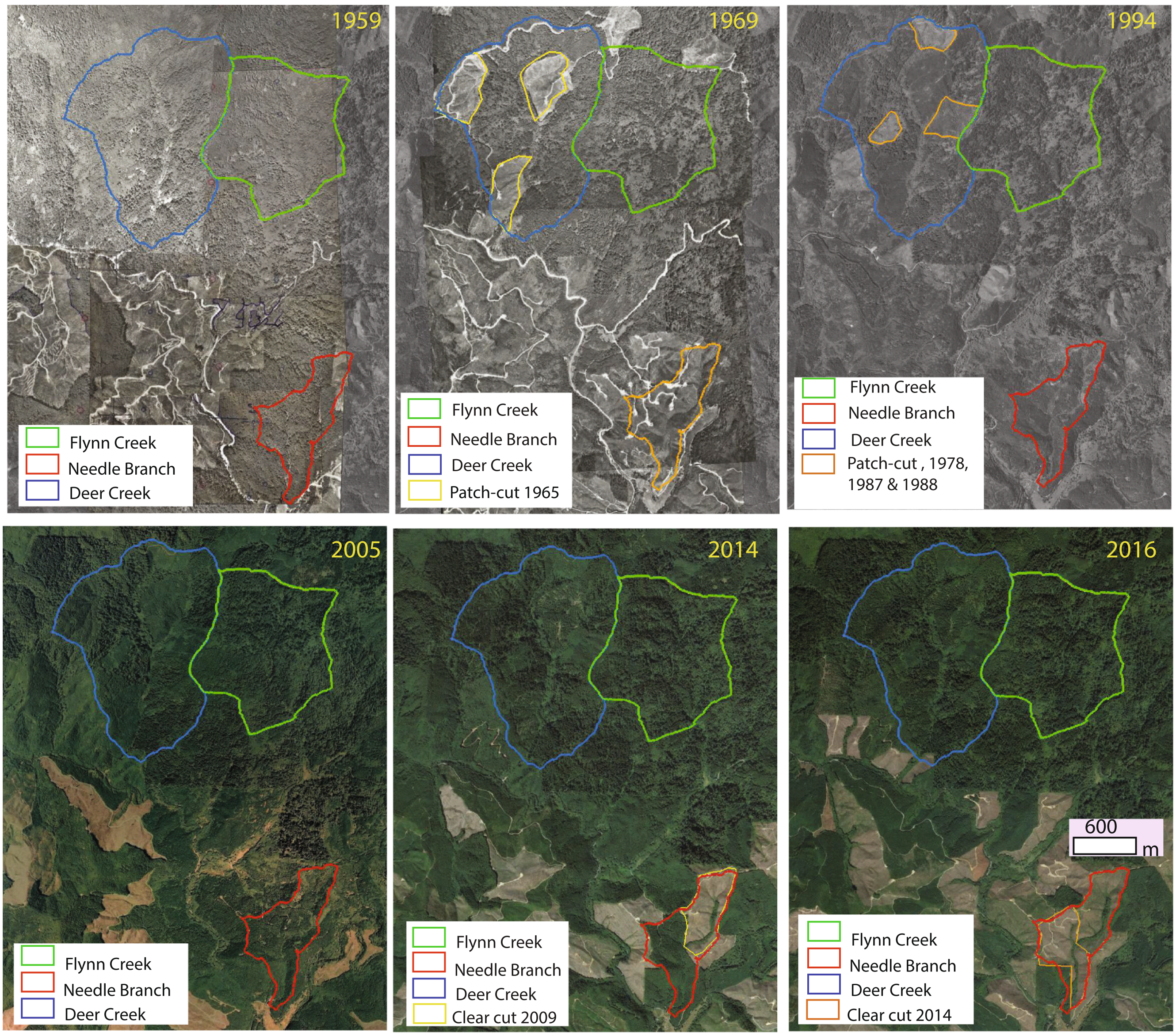

Fig. 2. Aerial view of the Alsea Watershed Study in 1959 (pre-first harvest entry), 1969 (post-first harvest entry), 1994 (post-thinning from 1978 to 1988 in Deer Creek), 2005 (pre-second harvest entry), 2014 (post-second harvest entry, Phase I), and 2016 (post-second harvest entry, Phase II).

were similar to the first entry pre-harvest period (1959–1965), and (2) to compare the effects of the first and second harvest entries on water yields (see Supplemental Material Tables S2–S4 and Figs. S3–S6).

Changes in daily streamflow from the Alsea Watershed Study were also compared to long-term watershed experiments in the Cascades of Oregon that used the same methods of analysis (Jones and Post, 2004; Perry and Jones, 2017).

4.3. Uncertainty

To account for uncertainty in drainage area and rating curves, estimated annual water yields for the historic and contemporary periods were compared, assuming different combinations of estimated drainage area and rating curves (Supplementary Material, Table S4). Based on this analysis we opted to use the lidar-derived drainage area estimates and the rating curves specific to the historic and contemporary periods (Method 1 in the Supplementary Material C).

We note that the Alsea Watershed Study gauging infrastructure was not designed and constructed to provide high resolution low flow measurements, but rather to capture the range of streamflow generated in these headwater watersheds. However, we believe that this infrastructure was sufficiently robust to detect long-term changes in daily flows. The Supplementary Material provides a comprehensive effort to confirm that these analyses are robust.

5. Results

Here we report analyses of effects on daily streamflow from (1) the historical (first entry) harvest in Deer Creek (25% patch clearcut of ~ 110-yr forest with riparian buffers) and Needle Branch (82% clearcut of ~ 110-yr forest with no riparian buffer), (2) 40–51-yr old forest plantation growth in Deer Creek and 40–61-yr old forest plantation in Needle Branch (including areas clear cut in 1956 and 1966), and (3) the contemporary harvest (second entry) in Needle Branch (96% clearcut of 43–58 yr-old plantation with riparian buffer) (Table 2).

Analysis of streamflow data from Flynn Creek (reference) indicated that streamflow at the long-term reference site was stationary. In other words, there was no evidence that daily streamflow had changed over the period of record (1959 to 2017) in the reference watershed, except

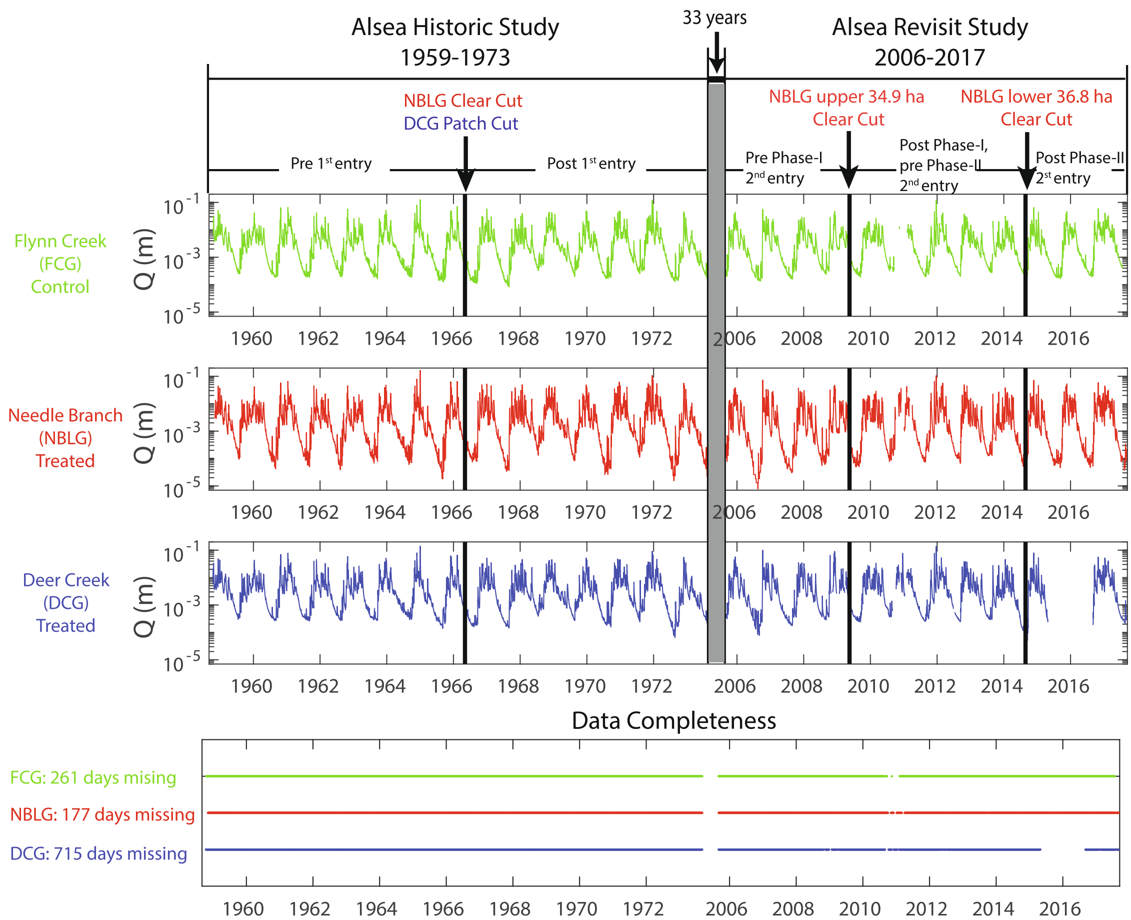

Fig. 3. Available discharge record in Flynn Creek Gauge (FCG), Needle Branch Gauge (NBLG), and Deer Creek Gauge (DCG) between water years 1959 and 2017. The historical harvest occurred in 1966 and the contemporary harvest occurred in 2009 (Phase I) and 2014 (Phase II).

for one day in early February when mean daily streamflow decreased by ~2% (p = 0.038; Supplementary Material Fig. S7). While changes associated with ongoing forest succession in Flynn Creek, such as senescence of riparian alder, were observed anecdotally, they did not produce detectable changes in streamflow over time at Flynn Creek, and therefore did not appear to affect the changes quantified in this study.

The comparisons of daily flows are presented here in terms of percent difference in ratios of the treatment to reference flows (Eq. (2)). The changes are presented in absolute differences in unit-area streamflow (mm) in the Supplementary Material B (Fig. S2).

5.1. Effects of initial harvest of ~110-yr-old forest on daily streamflow

Clearcutting of ~110-yr-old forest in 1966 initially increased streamflow (Table 2). During the first seven years after clearcutting in 1966, daily streamflow increased, on average, by 19% in Needle Branch (82% clearcut) and 6% in Deer Creek (25% patch clearcut) (Fig. 5 A, Table 2). On average, mean daily streamflow increased significantly on 235 days of each water year (64% of the days) in Needle Branch and 186 days of each water year (51%) in Deer Creek during the first seven years after clearcutting. The 82% clearcut harvest in Needle Branch primarily affected streamflow during the fall, producing increases of 60% (range: 26–98%) in daily streamflow from late September through November, with smaller (14%) increases in the spring (May 15 to June 30) and small decreases (-10%) in summer (July 1 to September 15) (Fig. 5 A, red line). The 25% patch clearcutting of ~ 110-yr-old forest in Deer Creek in 1966 also primarily affected daily streamflow in the fall (up to 30% increases in mid-September to mid- November) and late spring (up to 25% increases in June) (Fig. 5 A, blue line).

Table 2
Percent (%) change in streamflow in the harvested watersheds relative to the reference watershed (Flynn Creek) by time period after clearcutting of ~110-yr old forests, growth of 40- to 53-yr-old forest plantations, and clearcutting of 43–58-yr-old forest plantations in the Alsea watersheds.

Treated watershed	Time period	% change relative to first pre-treatment period (1959–1965)		% change relative to second pre-treatment period (2006–2009)	
		Water year	June 1- Sept 15	Water year	June 1–Sept 15
Needle Branch (82% clearcut[1])	1967–1973	19 (−20 to 98)	−3 (−20 to 24)	–	–
Needle Branch (82% plantation[1])	2006–2009	−25 (−59 to 29)	−50 (−59 to −35)	–	–
Needle Branch (48% clearcut)	2010–2014	0 (−35 to 60)	−21 (−35 to 18)	53 (−26 to 179)	76 (47 to 126)
Needle Branch (96% clearcut)	2015–2017	−6 (−49 to 46)	−36 (−49 to −8)	41 (−27 to 141)	49 (−3 to 141)
Deer Creek (25% patch clearcut)	1966–1973	6 (−12 to 31)	4 (−12 to 25)	–	–
Deer Creek (25% plantation)	2006–2017	−3 (−28 to 18)	−14 (−27 to 12)	–	–

[1] 13 ha in the headwaters of Needle Branch had been logged in 1956 (Hall and Stednick, 2008).

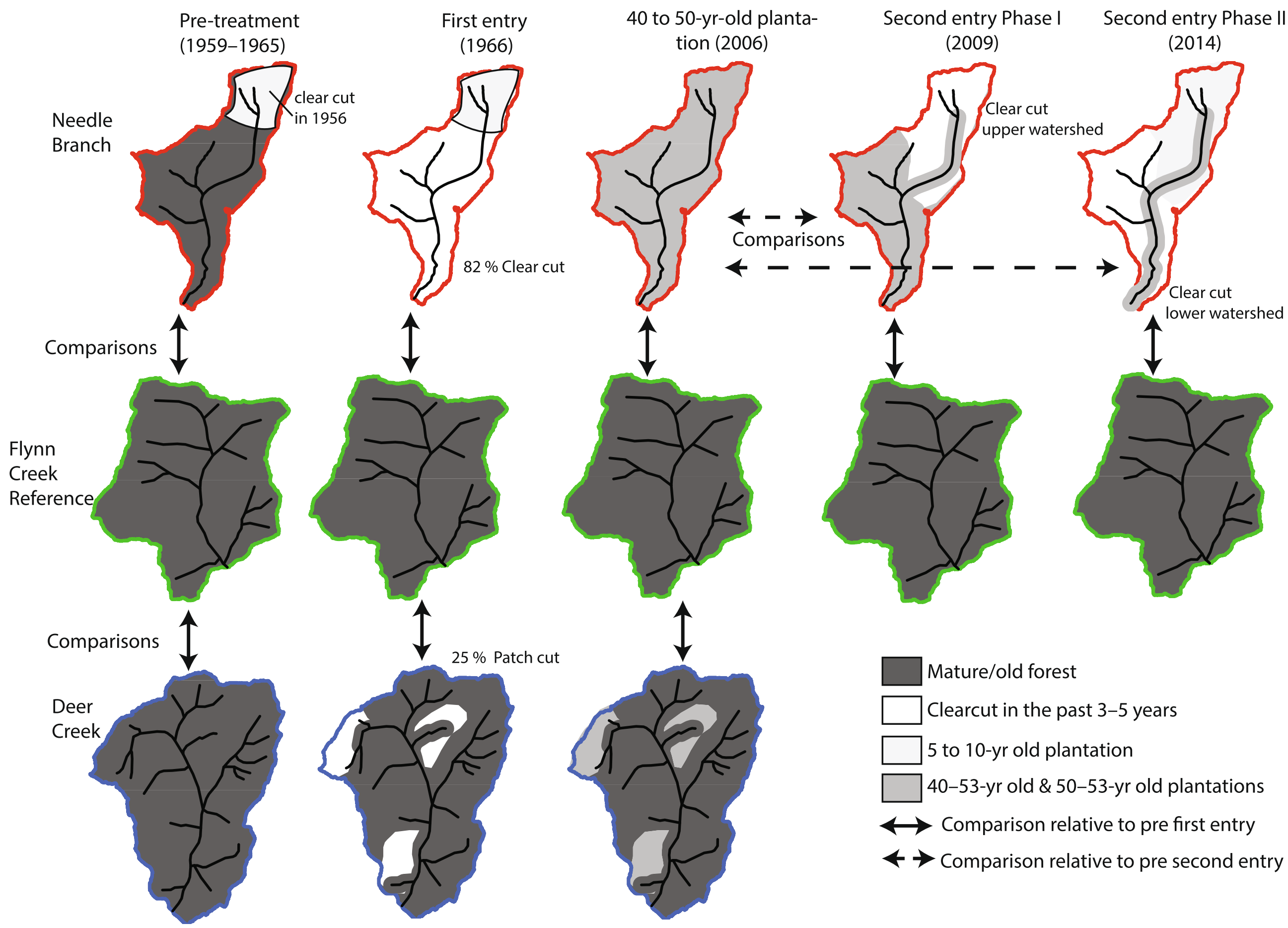

Fig. 4. A figure illustrating the different time periods and treatments used for comparisons of daily streamflow between the two harvested and replanted watersheds (Needle Branch, Deer Creek) relative to the reference watershed (Flynn Creek). The changes in streamflow associated with these comparisons are summarized in Table 2 and Figs. 5 and 6.

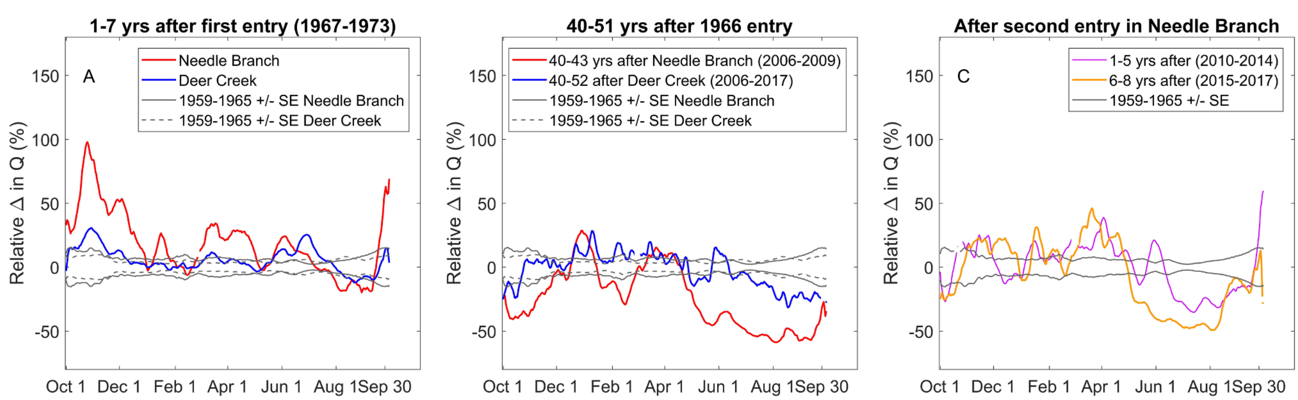

Fig. 5. Change in mean daily streamflow relative to the pre-harvest period (1959–1965) relationship with Flynn Creek (reference). Zero on the y-axis indicates no change in daily streamflow relative to the pre-treatment (1959–1965) relationship between the harvested watershed (Needle Branch, Deer Creek) relative to the reference watershed (Flynn Creek). A: 1 to 7 years after (1967–1973) in Needle Branch and Deer Creek; B: 40–43 years after (2006–2009) in Needle Branch and 40–52 years after (2006–2017) in Deer Creek; and C: Needle Branch 1–5 years after (2010–2014) second entry Phase I and 1–3 years after (2015–2017) second entry Phase II.

5.2. Long-term effects of plantations forest on daily streamflow

Replacement of ~110-yr-old conifer forest with 40–53-year-old plantations decreased daily streamflow in Needle Branch and Deer Creek (Table 2). During 2006–2009, the period 40–43 years after 82% harvest and 50–53 years after 17% harvest and planting of Douglas-fir in Needle Branch, daily streamflow was, on average, 25% lower than the reference watershed (Fig. 5 B, red line). In contrast, 40–51 years after 25% harvest and planting of Douglas-fir in Deer Creek (2006–2017), mean daily streamflow was, on average, 3% lower than the reference watershed (Fig. 5 B, blue line).

Decreases in streamflow were greatest during the summer low flow period (Fig. 5 B, Table 2). During the period 40–43 years after 82% harvest (and 50–53 years after 17% harvest) and planting of Douglas-fir in Needle Branch, mean daily streamflow between June 1 to September 15 was 50% lower than the reference watershed (Fig. 5 B, red line). In

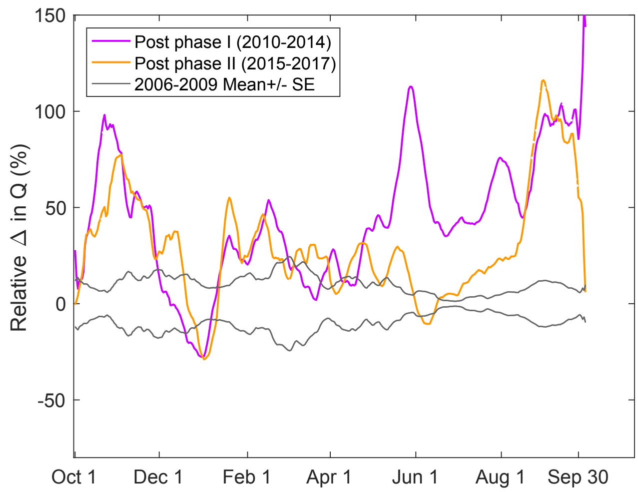

Fig. 6. Relative change in mean daily streamflow between the reference watershed (Flynn Creek) and the harvested watershed (Needle Branch) between the pre-harvest period of the second entry (2006–2009) and the post-harvest periods, 2010–2014 (1–5 years after second entry Phase I) and 2015–2017 (1–3 years after second entry Phase II).

contrast, 40–51 years after 25% harvest and planting of Douglas-fir in Deer Creek, mean daily streamflow during June 1 to September 15 was 14% lower than in the reference watershed (Fig. 5 B, blue line).

5.3. Effect of the second harvest on daily streamflow

After the first (2009) and second (2014) phases of the contemporary harvest period (second entry) in Needle Branch, daily streamflow increased relative to the pre-harvest 40- to 53- yr-old forest plantation conditions, but summer streamflow deficits persisted (Table 2, Fig. 5 C, orange and magenta lines). When compared to the second pre-harvest period (2006–2009), mean daily streamflow in Needle Branch increased by 53% in the first five years (2010–2014) after Phase I of the second harvest (Fig. 6, magenta line). These increases occurred on average during 308 days of each water year. The highest increases in daily flows after Phase I of the second entry (2010–2014) occurred in the late summer (Table 2, Fig. 6, magenta line). Also, when compared to the second pre-harvest period (2006–2009), mean daily streamflow increased by 41% in the first three years after Phase II of the second harvest (2015–2017) and increases occurred on average during 320 days of each water year (Fig. 6, orange line). Relative increases in streamflow were greater after the harvest of the young forest plantation than after the harvest of mature/old forest (Table 2).

Over the water year as a whole, the second harvest did not restore streamflow to the levels produced by mature/old forest in the reference watershed. When compared to the initial pre-harvest period (1959–1965), mean daily streamflow in Needle Branch was unchanged (0% change) in the first five years (2010–2014) after Phase I of the second harvest, and it was 6% lower in the three years (2015–2017) after Phase II of the second harvest entry (2014) (Fig. 5 C orange and magenta lines, Table 2).

Summer streamflow increased after the harvest of 43- to 53-yr-old plantation forests, but then quickly declined, and remained lower than summer streamflow in the mature/old forest reference watershed. That is, relative to the second pre-harvest period (2006–2009; 40–53-yr-old plantations), June 1 to September 15 streamflow increased by 76% in the first five years after Phase I of the second harvest (2010–2014) and by 49% in the first three years after Phase II of the second harvest (2015–2017) (Fig. 6, orange and magenta lines). In contrast, relative to the first pre-treatment period (1959–1965; 110-yr-old forest), mean daily streamflow during June 1 to September 15 decreased by 21% in the first five years (2010–2014) after Phase I of the second harvest and decreased by 36% in the first three years (2015–2017) after Phase II of the second harvest (Fig. 5 C, orange and magenta lines). After the second harvest, streamflow from the harvested watershed was significantly lower than in the reference watershed for an average of 138 days of each water year between 2010 and 2014 and 168 days of each water year between 2015 and 2017 (Fig. 5 C, orange and magenta lines). In other words, the combination of 1- to 3-yr-old Douglas-fir plantation in the lower half of Needle Branch, 5 to 8-yr-old plantation in the upper half of the watershed, and 49- to 61-yr-old Douglas-fir and red alder in the riparian buffer zone produced similar summer streamflow levels to the 40- to 53-yr-old plantation (Table 2).

5.4. Comparison with other long-term paired watershed studies in the region

The observed 50% declines in summer streamflow from 40- to 53-yr-old Douglas-fir plantations at Needle Branch, relative to the mature/old forest reference watershed, were comparable to those detected for similar aged Douglas-fir plantations in the H.J. Andrews Experimental Forest (Watershed 01, AND1) and the Coyote Creek (Coyote 03, COY3) watersheds in the Oregon Cascades (Fig. 7 A). Summer streamflow

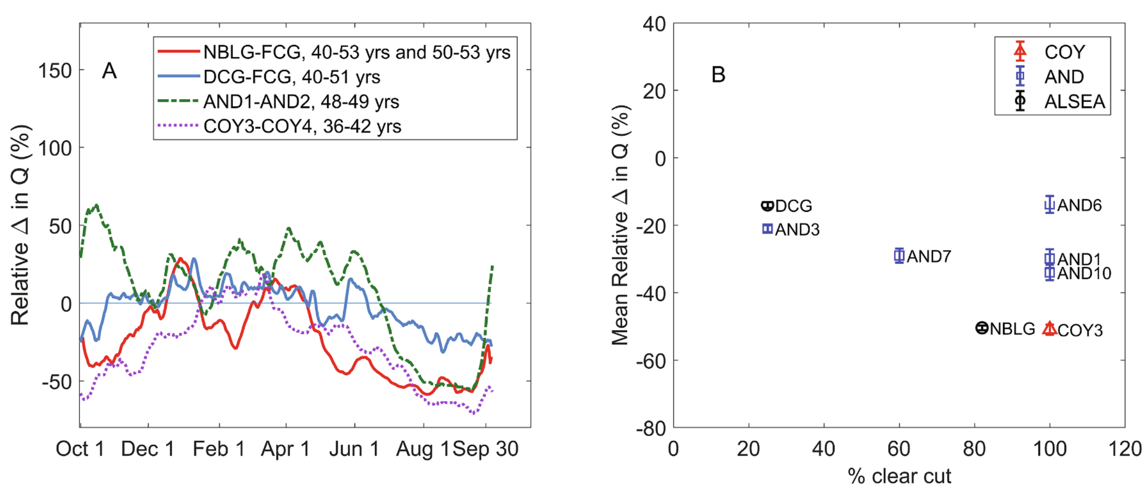

Fig. 7. (A) Relative change in mean daily flows between the reference watersheds (Flynn Creek, FCG, AND2, and COY4) and 100% clearcut watershed covered with 36–53-yr old plantations (NBLG, AND1, and COY3) in the Alsea (FCG, NBLG), the H.J. Andrews Experimental Forest (AND2 and AND1), and Coyote Creek Experimental forest (COY3 and COY4). Also 25% patch cut watersheds in Alsea (FCG, DCG) (B) Mean summer (June 1–September 15) relative change in daily flows between reference and treated watersheds versus percent clear cut in 35–53-yr old forests.

deficits were more persistent in Needle Branch (May to December) and in COY3 (May to November) than in AND1 (June to September) (Fig. 7 A). The magnitude of summer streamflow deficits also was related to the proportion of watershed area in young (30- to 50-yr-old) plantations in several of the paired watersheds at the H.J. Andrews, Coyote Creek, and Alsea (Fig. 7 B) (Jones and Post, 2004; Perry and Jones, 2017). In particular, 82–100% cover of Douglas-fir plantations ranging from 36 to 53 years of age in Needle Branch, AND1, and COY 3 produced summer daily streamflow deficits of 30 to 51% relative to their mature and old-growth forest reference watersheds. In contrast, 25% cover of Douglas-fir plantations in Deer Creek and AND3 produced summer daily streamflow deficits of 14–21%. Controlling for area of mature forest converted to plantations, summer streamflow deficits were smaller in the Andrews Forest compared to Alsea and Coyote (Fig. 7 B).

6. Discussion

The long-term streamflow responses observed in the Alsea Watershed Study, along with results from other studies in the region, suggest that the effects of vegetation on evapotranspiration strongly influence summer low flows. However, these effects may be moderated by climate variability. In conjunction with other published work from the Alsea Watershed Study, these results also indicate that summer low flow deficits associated with contemporary plantation forestry, using ~40- to 50-yr rotations and riparian buffers, may limit fish habitat. These findings are discussed in detail below.

6.1. Vegetation effects on evapotranspiration

The age, species composition, density, and successional stage of vegetation appeared to affect evapotranspiration, explaining many of the observed streamflow responses. The 40- to 53-yr-old forest plantations produced summer low flow deficits in Needle Branch because of apparently higher transpiration of young trees, growing in dense, plantation forest stands, compared to large, mature/old trees growing in less dense stands shaped by centuries of disturbance and succession. The greater relative increase in streamflow after the harvest of the young forest plantation compared to increases after the initial harvest of mature/old forest in Needle Branch (Table 2) indicates that the evapotranspiration rates in the 40- to 53-yr old forest plantation were substantially greater than in the primarily older forest that had been harvested in 1966. Similar to other studies in the region that also included historic harvesting (with no riparian buffers), the magnitude of summer streamflow deficits in Needle Branch were proportional to the area of watershed in young forest plantations (Fig. 7 B). This provides evidence indicating that the effects of forest harvesting on evapotranspiration were additive in these headwater catchments (< 3 km^2).

These findings are consistent with literature suggesting that transpiration rates decrease with age in individual trees and as a result of changes in forest structure during succession. Immediately after clear-cutting, reductions in interception and evapotranspiration generally lead to increased soil moisture and increased streamflow (Bowling et al., 2000; Harr et al., 1982; Keppeler and Ziemer, 1990; Rothacher, 1965). However, over time vegetation regeneration can increase evapotranspiration and decrease soil moisture and summer streamflow (Adams et al., 1991; Fowler et al., 1987; Ingwersen, 1985; Pike and Scherer, 2003; Salemi et al., 2012). Young, fast-growing, densely spaced trees typically have higher rates of sapflow compared to older forest stands (Moore et al., 2004; Moore et al., 2011; Perry and Jones, 2017), which could contribute to summer streamflow deficits. For example, streamflow deficits declined in South African watersheds as forest plantations exceeded their rotation ages ($>$ 15 yrs for *Eucalyptus grandis* and $>$ 30 yrs for *Pinus radiata*) (Scott and Prinsloo, 2008). Similarly, stem density, stomatal conductance, and photosynthesis decreased in 70–100-yr old compared to 20–40-yr-old loblolly pine stands (Drake et al., 2011), indicating that tree physiological changes during later stages of forest succession may decrease summer evapotranspiration and may increase summer streamflow in mature/old forests. Summer streamflow deficits under 40- to 53-yr old plantations at Needle Branch (Alsea) were comparable in magnitude to those reported from similar aged Douglas-fir plantations in other paired watersheds in Oregon (Andrews Forest, Coyote Creek) (Jones and Post, 2004; Perry and Jones, 2017) indicating that Douglas-fir plantations of similar age have similar evapotranspiration rates relative to the mature/old and Old-growth forest reference stands in each of these three locations.

Contemporary forest practices (clearcut harvest of 43- to 53-yr-old plantations with a riparian buffer) at Alsea did not restore summer low flows to levels produced by mature/old forest. Forest harvesting, with riparian buffers, in the upper half of Needle Branch in 2009 increased summer low flows relative to the pre-harvest plantation, but these flows were still lower than those in the reference mature/old forest. This response implies relatively high evapotranspiration by the remaining 44- to 58-yr-old Douglas-fir plantations in the lower half of the watershed and the trees in the riparian buffer zone in the upper watershed, compared to the mature/old forest in the reference watershed.

Surprisingly, after the remainder of Needle Branch was clearcut with a riparian buffer in 2014, summer streamflow deficits intensified and approached those under the former 40- to 53-yr-old plantations. This response implies high evapotranspiration from the upper part of the watershed with 6- to 8-yr-old Douglas-fir and from residual trees in the riparian buffer zone, suggesting that this vegetation can exert a disproportionate effect on low streamflow (Bond et al., 2002), while representing only a few percent of watershed area.

6.2. Effects of climate variability on low streamflow

Both spatial and temporal variation in climate appeared to affect the magnitude and duration of summer low flow deficits. Summer streamflow deficits at Alsea were of similar duration to those from Coyote Creek in the southern Oregon Cascades, but lasted for more of the year than those reported from similar aged Douglas-fir plantations in the H.J. Andrews Forest in the central Oregon Cascades (Jones and Post, 2004; Perry and Jones, 2017). In addition, controlling for plantation area harvested, summer streamflow deficits were smaller at the H.J. Andrews Forest compared to the Alsea and Coyote Creek (Fig. 7 B). The first seven years after the initial harvest of mature/old forest in Needle Branch (in the 1960s) produced much smaller increases in average daily streamflow and summer streamflow than reported for other paired watershed studies in Oregon, New Hampshire, and North Carolina (Jones and Post, 2004; Perry and Jones, 2017). These differences may be explained in part by potentially high evapotranspiration demand from the re-growing vegetation in the 13 ha that were clear-cut in Needle Branch in 1956, cooler winter temperatures and the presence of snowpack at the Andrews Forest, seasonal snowpack and deciduous forests at Hubbard Brook (in New Hampshire), and deciduous forests at Coweeta (in North Carolina) (Jones and Post, 2004). All of these factors may limit the period of summer deficits in these sites, compared to locations with less snow, warmer winter temperature, and evergreen forest, such as the Alsea or Coyote study sites.

Temporal variation in climate also may have influenced the magnitude and duration of summer streamflow deficits in Needle Branch after the second harvest (2010–2017). Summer streamflow deficits intensified unexpectedly after Phase II of logging during the second harvest at Needle Branch (2015–2017). Summer conditions were hotter and drier in Phase II (2015–2017) compared to Phase I (2010–2013) (see study site description). Controlling for plantation age, summer low flow deficits were greater under plantations relative to reference old-growth forest during hotter, drier years, when summer streamflow was relatively low (Perry and Jones, 2017). Streamflow responses to clearcutting of old-growth and establishment of Douglas-fir plantations (Andrews AND1 and AND2) varied significantly between dry and wet periods (Burt et al., 2015). The hotter, drier conditions in 2015 to 2017 may have intensified evapotranspiration in the remaining vegetation, overwhelming any increases in moisture after logging of the lower watershed in Needle Branch.

6.3. Implications for water quality and fish habitat

Persistent deficits in summer low flows related to plantation forestry have the potential to impact water quality and aquatic ecosystem health. For example, maximum daily stream temperatures in Needle Branch rose by 7–15 °C in the first two years after clearcutting of mature/old forest, removal of riparian vegetation and instream wood, and burning of slash in the 1960s (Brown and Krygier, 1970). These stream temperature increases occurred despite an increase in streamflow and are similar to increases reported elsewhere (e.g., Johnson and Jones, 2000). In contrast, the second harvest in 2009 (of 43-to 53-yr-old plantation) had little effect on stream temperature (Bladon et al., 2016). The lack of a stream temperature response to the second harvest is likely related to the riparian buffer (i.e., mean canopy closure over the stream was 96% before the harvest and 89% after the harvest), the relative post-harvest increase in daily streamflow we reported in this study (50–180%), and the groundwater and hyporheic sources of summer streamflow in the watershed (Hale and McDonnell, 2016).

Salmonid fish biomass in Needle Branch appeared to have recovered to the pre-treatment 1959–1965 levels prior to the second entry, and late-summer total biomass of coastal cutthroat trout increased after harvest of the 43- to 53-yr old plantation (Bateman et al., 2018). The reported 76% relative increases in summer streamflow between 2010 and 2014 and associated increases in stream perennial extent and available habitat following the second harvest may partially explain the increase in fish biomass after the second entry Phase I. However, it remains uncertain why fish biomass recovered to original levels when streamflow was reduced under the 40- to 53-yr-old forest stand. Some models suggest a 25–50% reduction in fish habitat availability as a result of decreased summer low flow associated with regenerating young stands (Gronsdahl et al., 2019). Research at the Alsea Watersheds and elsewhere should continue to monitor fish response to changing forest and stream conditions.

7. Conclusion

Streamflow from a 40- to 53-yr-old Douglas-fir plantation in the Alsea watershed in the Coast Range of Oregon was 25% lower on average and 50% lower during the summer (June 1 to September 15), relative to the reference watershed containing mature/old forest. These low flow deficits were similar in magnitude to those observed under similar-aged Douglas-fir plantations in the Cascade Range of Oregon. High evapotranspiration rates from Douglas-fir plantations appeared to explain deficits from 40- to 50-yr-old forest plantations. Surprisingly, contemporary forest practices (i.e., clearcut of 43- to 53-yr-old and 48- to 58-yr-old plantations with riparian buffers) had only a minor effect on the streamflow deficits, and by a few years after logging, summer streamflow deficits were similar to those observed under 40- to 53-yr-old plantations. High evapotranspiration from rapidly regenerating vegetation, including planted Douglas-fir, and from the residual forest in the riparian buffer appeared to explain the persistence of streamflow deficits despite nearly 100% clearcutting of the watershed. Low streamflow deficits also were greater during warmer, drier years. Results of this study indicate that contemporary forestry harvesting practices, including 40- to 50-yr rotations of Douglas-fir plantations with riparian buffers, may produce persistent low flow deficits. Short-term amelioration of these deficits after logging may partially explain observed increases in fish biomass in Needle Branch; however, it remains uncertain why fish biomass appeared to have recovered in the 40- to 53-yr-old forest stand to levels observed in 1958–1973. Further work is needed to examine how intensively managed plantation forests and expected warmer, drier future conditions may influence summer low streamflow and aquatic ecosystems.

Credit authorship contribution statement

Catalina Segura: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Writing - original draft, Funding acquisition. **Kevin D. Bladon:** Conceptualization, Writing - review & editing, Funding acquisition. **Jeff A. Hatten:** Conceptualization, Writing - review & editing, Funding acquisition. **Julia A. Jones:** Conceptualization, Writing - review & editing, Funding acquisition. **V. Cody Hale:** Writing - review & editing. **George G. Ice:** 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.jhydrol.2020.124749.

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