Oregon Stream Protection Coalition

BEFORE THE OREGON BOARD OF FORESTRY
Statement of Mary Scurlock
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Agenda Item 7: State Forest Management Plan

I am Mary Scurlock for the Oregon Stream Protection Coalition, a federation of twenty-five conservation and fishing organizations supporting my advocacy to protect freshwater ecosystems on Oregon's nonfederal forest landscape.

I appreciate the Board's thoughtful conversation around state forests today, and especially your commitment to consideration of best available science to develop a durable management plan that integrates the state's goals for management of state forests' valuable natural resources and merits federal assurances under the Endangered Species Act.

Today I'd like to highlight significant recent findings about the relationship between forest management and water flows that were the subject of an April 4 conference at the Pacific Northwest Research Station in Corvallis entitled "Summer Low Flows in Western Oregon: Processes, Trends, Uncertainties, and Forest Management." The meeting was organized by the Research Station, BLM, Weyerhaeuser Company and NCASI.

Tim Perry and Julia Jones of OSU published a study in 2016 that analyzed long-term paired watershed data from experimental forests in Oregon. (Enclosed). The results extend and sharpen previous analyses of post-logging effects on instream flow, concluding that after an initial 10-15 year period of increased baseflows (late spring, summer and early fall), stream flows are reduced by about 50% for a period lasting from 15 to at least 50 years. These persistent low flows resulted where more than half the catchment area was logged – that is, where less than half the watershed area remained in mature and old growth forest. The ultimate timeframe for return to the higher base flow conditions observed before logging remains unknown. It could be 60 years, or it could be 120, or more.

The hydrologic explanation for low flow depletion appears to be increased evapotranspiration in second-growth forests due to greatly reduced water use efficiency and also, possibly, increased physical evaporation (from soil, or from condensation on the outside of foliage, etc.) in second-growth compared to mature and old growth conifer forests. The relatively consistent and sustained low flow deficits among the study basins supports the applicability of the results to logged watersheds across the Pacific Northwest, particularly where Douglas fir is the dominant tree species.

A key take home message from the conference is that not only are the findings of the Perry and Jones (2017) study broadly relevant to forest managers, but not one of the paper's findings or speculative discussion points were scientifically challenged at the meeting. Given the credibility of this new science, this Board will have to grapple with its implications in a variety of policy forums, including in state forest planning in basins where ODF is majority owner such as the Trask, Kilchis, and Wilson rivers.

Other important take-aways from the conference are:

- It's not just small headwater streams that are affected by persistent low flows; in most cases streamflow decreases in most cases will aggregate to reduce flows downstream;
- We can't prevent or even mitigate for flow depletion with riparian buffers
- Modified harvest practices like thinning or staggered short-rotation clearcuts are also likely to be ineffective at reducing or mitigating depletion of streamflows;
- Past widely-cited textbook claims and assumptions in agency plans and assessments of a 10-15 year "hydrologic recovery" after clearcut logging are fundamentally wrong and do not represent current science.

We strongly support more research to better predict, understand and prevent the low flow effect, but available science is indisputable that the effect real. The management implications seem clear: if we truly want to conserve water and the species and human communities that depend on it for life in an era of climate change, more short-rotation logging is not in the cards. More older forests and longer-rotation forestry will be needed to protect and stabilize water flows.

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SPECIAL ISSUE PAPER

Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA

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Abstract

Despite controversy about effects of plantation forestry on streamflow, streamflow response to forest plantations over multiple decades is not well understood. Analysis of 60-year records of daily streamflow from eight paired-basin experiments in the Pacific Northwest of the United States (Oregon) revealed that the conversion of old-growth forest to Douglas-fir plantations had a major effect on summer streamflow. Average daily streamflow in summer (July through September) in basins with 34- to 43-year-old plantations of Douglas-fir was 50% lower than streamflow from reference basins with 150- to 500-year-old forests dominated by Douglas-fir, western hemlock, and other conifers. Study plantations are comparable in terms of age class, treatments, and growth rates to managed forests in the region. Young Douglas-fir trees, which have higher sapwood area, higher sapflow per unit of sapwood area, higher concentration of leaf area in the upper canopy, and less ability to limit transpiration, appear to have higher rates of evapotranspiration than old trees of conifer species, especially during dry summers. Reduced summer streamflow in headwater basins with forest plantations may limit aquatic habitat and exacerbate stream warming, and it may also alter water yield and timing in much larger basins. Legacies of past forest management or extensive natural disturbances may be confounded with effects of climate change on streamflow in large river basins. Continued research is needed using long-term paired-basin studies and process studies to determine the effects of forest management on streamflow deficits in a variety of forest types and forest management systems.

KEYWORDS

climate change, native forests, plantations, stationarity, succession, water scarcity

1 | INTRODUCTION

Widespread evidence that streamflow is declining in major rivers in the United States and globally has raised concerns about water scarcity (Adam, Hamlet, & Lettenmaier, 2009; Dai, Qian, Trenberth, & Milliman, 2009; Luce & Holden, 2009; Vörösmarty, Green, Salisbury, & Lammers, 2000). Climate change and variability are implicated as causes of many streamflow trends (Lins & Slack, 1999, 2005; McCabe & Wolock, 2002; Mote et al., 2003; Hodgkins, Dudley, & Huntington, 2003, 2005; Stewart, Cayan, & Dettinger, 2004, 2005; Nolin & Daly, 2006; Hamlet & Lettenmaier, 2007; Barnett et al., 2008; Jefferson, Nolin, Lewis, & Tague, 2008; Lara, Villalba, & Urrutia, 2008; Dai et al., 2009; Kennedy, Garen, & Koch, 2009; Jones, 2011). However, large-scale plantation forestry, often using non-native tree species, is expanding in much of the temperate zone on Earth, despite widespread evidence that intensive forestry reduces water yield (Cornish & Vertessy, 2001; Andréassian, 2004; Brown, Zhang, McMahon, Western, & Vertessy, 2005, Farley, Jobbágy, & Jackson, 2005; Sun et al., 2006; Little, Lara, McPhee, & Urrutia, 2009). Water yield reductions are greater in older plantations, during dry seasons, and in arid regions (Andréassian, 2004; Brown et al., 2005; Farley et al., 2005; Sun et al., 2006). Yet, downstream effects of forestry are debated (van Dijk & Keenan, 2007).

Despite general studies of water partitioning in forested basins (e.g., Budyko, 1974, Zhang, Dawes, & Walker, 2001, Jones et al., 2012), it is unclear how streamflow varies during forest succession, relative to tree species, age, or growth rates in native forest and forest plantations (Creed et al., 2014). In the Pacific Northwest of the United States, forest plantations have reduced summer streamflow relative to mature and old-growth forest (Hicks, Beschta, & Harr, 1991; Jones & Post, 2004). However, the magnitude, duration, causes, and consequences of summer water deficits associated with forest plantations are not well understood.

In the Pacific Northwest, large areas of old-growth forest have been converted to forest plantations. We examined how changes in forest structure and composition have affected streamflow using multiple paired-basin experiments in western and southwestern Oregon, where regenerating forests are currently aged 40 to 50 years, and reference forests are aged 150 to 500 years. Many studies have reported on these experiments, including vegetation ecology (e.g., Marshall & Waring, 1984; Halpern, 1989; Halpern & Franklin, 1990; Halpern & Spies, 1995; Lutz & Halpern, 2006; Halpern & Lutz, 2013) and hydrology (e.g., Rothacher, 1970; Harr, Fredriksen, & Rothacher, 1979; Harr & McCorison, 1979; Harr, Levno, & Mersereau, 1982; Hicks et al., 1991; Jones & Grant, 1996, Jones, 2000; Jones & Post, 2004, Perkins & Jones, 2008; Jones & Perkins, 2010; Jennings & Jones, 2015). We asked:

1. How has daily streamflow changed over the past half-century in reference basins with 150- to 500-year-old forest?

TABLE 1 Name and abbreviation, area, elevation range, natural vegetation and vegetation age when streamflow records began, streamflow gaging method and record length, harvest treatment, logging methods, and treatment dates for basins used in this study

Basin name	Area (ha)	Elevation range (m)	Natural vegetation	Streamflow record length, instrumentation[b]	Treatment, date[a]	Logging method
Coyote 1 COY 1	69.2	750–1,065	Mixed conifer	1963–81 V; 2001–present V	Roads 1970; 50% overstory selective cut, 1971	Tractor yarded
Coyote 2 COY 2	68.4	760–1,020	Mixed conifer	1963–81 V; 2001–present V	Permanent roads 1970; 30% 2- to 3-ha patch cuts, 1971	16% high-lead cable yarded; 14% tractor yarded.
Coyote 3 COY 3	49.8	730–960	Mixed conifer	1963–81 V; 2001–present V	Permanent roads 1970; 100%; clearcut 1971	77% high-lead cable yarded; 23% tractor yarded.
Coyote 4 COY 4	48.6	730–930	Mixed conifer	1963–81 V; 2001–present V	Reference	N/A
Andrews 1 AND 1	95.9	460–990	450- to 500-year-old Douglas-fir forest	1952–present (1952–present T [rebuilt 1956]; 1999-present SV)	100% clearcut 1962–1966, broadcast burn 1966	100% skyline yarded
Andrews 2 AND 2	60.7	530–1,070	450- to 500-year-old Douglas-fir forest	1952–present (1952–present T; 1999–present SV)	Reference	N/A
Andrews 3 AND 3	101.2	490–1,070	450- to 500-year-old Douglas-fir forest	1952–2005 T; 1999–present SV	Roads 1959; 25% patch cut 1962, broadcast burn 1963	25% high-lead cable yarded
Andrews 6 AND 6	13.0	863–1,013	130- to 450-year-old Douglas-fir forest	1964–present; (1964–1997 H; 1997–present T; 1998 present SV)	Roads, 1974; 100% clearcut 1974; broadcast burn 1975	90% high-lead cable yarded; 10% tractor yarded
Andrews 7 AND 7	15.4	908–1,097	130- to 450-year-old Douglas-fir forest	1964–1987; 1995–present (1964–1997 H; 1997–present T; 1998–present SV)	Roads 1974; 60% shelterwood cut 1974; remaining overstory cut 1984; broadcast burn lower half of basin 1975; 12% basal area thin 2001	40% skyline yarded; 60% tractor yarded.
Andrews 8 AND 8	21.4	955–1,190	130- to 450-year-old Douglas-fir forest	1964–present (1964–1987 H; 1987 present T; 1973–1979 SV, 1997–present SV)	Reference	N/A
Andrews 9 AND 9	9	425–700	130- to 450-year-old Douglas-fir forest	1969–present (1969–1973 H; 1973 present T; 1973–1979 SV, 1997 present SV)	Reference	N/A
Andrews 10 AND 10	10	425–700	130- to 450-year-old Douglas-fir forest	1969–present (1969–1973 H; 1973 present T; 1973–1979 SV, 1997–present SV)	100% clear-cut 1975; no burn	100% high-lead cable yarded

Sources: Harr et al., 1979; Rothacher, 1965; Harr et al., 1982; Rothacher, Dyrness, & Fredriksen, 1967; Jones & Post, 2004.

[a]Broadcast burns were controlled burns over the cut area intended to consume logging debris.

[b]H = H-flume; T = trapezoidal flume; V = V-notch weir or plate. Summer V-notch weirs (SV) have been used for improved discharge measurements over the following periods: since 1999 at Andrews 1, 2, and 3; since 1998 at Andrews 6, 7, and 8; and from 1969 to 1973 and since 1997 at Andrews 9 and 10.

2. What are the trends in daily streamflow over 40- to 50-year periods, from basins with regenerating forests compared to reference basins?
3. How are changes in summer streamflow related to forest structure and composition in mature and old-growth forests versus forest plantations?

2 | STUDY SITE

The study examined streamflow changes in eight pairs of treated/reference basins in five paired-basin studies. Five of the basin pairs (eight basins) were located in the H.J. Andrews Experimental Forest (122°15′W, 44°12′N) in the Willamette National Forest. Three basin pairs (four basins) were located at Coyote Creek in the South Umpqua Experimental Forest (122°42′W, 43°13′N) in the Umpqua National Forest (Table 1; Figure 1). Basins are identified as Andrews 1, 2, etc. = AND 1, 2, etc.; Coyote 1, 2, etc. = COY 1, 2, etc. (Table 1).

The geology of the study basins is composed of highly weathered Oligocene tuffs and breccias that are prone to mass movements. The upper elevation portion of the Andrews Forest (above ~800 m, AND 6, AND 7, AND 8) is underlain by Miocene andesitic basalt lava flows (Dyrness, 1967; Swanson & James, 1975; Swanson & Swanston, 1977). Soils are loamy, well-drained, and moderately to highly permeable, with considerable variation in depth and rock content (Rothacher, 1969; Dyrness, 1969; Dyrness & Hawk, 1972).

The Andrews Forest ranges from 430 to 1,600 m elevation; study basins range from 430 to 1,100 m elevation (Table 1). Area-averaged slope gradients are >60% at low elevation (AND 1, AND 2, AND 3, AND 9, AND 10) and 30% at high elevation (AND 6, AND 7, AND 8). Mean daily temperature ranges from 2°C (December) to 20°C (July) at 430 m and from 1°C (December) to 17°C (July) at 1300 m. Mean annual precipitation is 2300 mm, >75% of precipitation falls between November and April, and actual evapotranspiration averages 45% of precipitation. The South Umpqua Experimental Forest (Coyote Creek basins) ranges from 730 to 1065 m elevation. Most slope gradients are <40% (Arthur, 2007). Mean daily temperature (at USHCN station OR356907, 756 m elevation, 30 km SE of Coyote Creek) ranges from 3°C (December) to 20°C (July). Mean annual precipitation (at OR356907) is 1,027 mm, >80% of precipitation falls between November and April, and actual evapotranspiration averages 45% of precipitation.

Study basins are located along a gradient of seasonal snow depth and duration (Harr, 1981, 1986). At high elevation (>800 m, AND 6, AND 7, and AND 8), average snowpack water equivalent on April 30 exceeds 700 mm (30% of annual precipitation), and snow may persist for 6 months, whereas at low elevation (<700 m, AND 9, AND 10), snow rarely persists more than 1–2 weeks and usually melts within 1–2 days; peak snowpack water equivalent is ~2% of precipitation

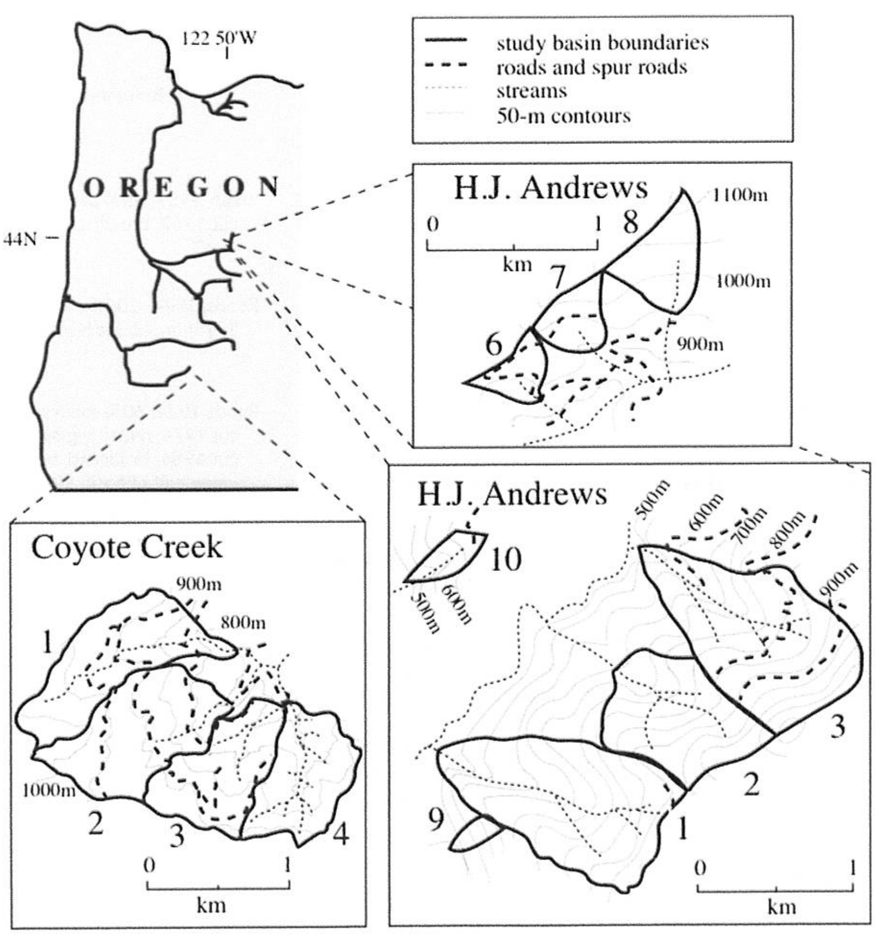

FIGURE 1 Location of study basins in western Oregon

(Harr et al., 1979; Harr & McCorison, 1979; Harr et al., 1982; Perkins & Jones, 2008). Snow at the South Umpqua Experimental Forest (Coyote Creek) usually melts within 1–2 weeks.

Vegetation at the Andrews Forest is Douglas-fir/western hemlock forest. Mature and old-growth forest regenerated after wildfires in the early 1500s and mid-1800s (Weisberg & Swanson, 2003, Tepley, 2010, Tepley, Swanson, & Spies, 2013). Overstory canopy cover is 70% to 80% and leaf area index is >8 (Dyrness & Hawk, 1972; Marshall & Waring, 1986; Lutz & Halpern, 2006). Vegetation at the South Umpqua Experimental Forest is mixed conifer (Douglas-fir, white fir, incense cedar, sugar pine), and overstory canopy cover is 70% to 80% (Anderson et al., 2013).

At the Andrews Forest, the first paired-basin experiment began in 1952 (AND 1, 2, 3); a second paired basin experiment began in 1963 (AND 6, 7, 8), and a third paired-basin experiment began in 1968 (AND 9, 10), with continuous records except at AND 7 (Table 1). Pre-treatment periods exceeded 7 years in all cases and were 10 years for AND 1/2, AND 6/8, and AND 7/8. Streamflow instrumentation changed in some basins over the period of record (Table 1). Because of the timing of instrumentation changes at AND 9/10, AND 2 is used as the reference basin for AND 10 (see Supporting Information). At the South Umpqua Experimental Forest, the Coyote Creek paired-basin experiment began in 1963 (Table 1). The pre-treatment period was 7 years. Despite a break in the record from 1981 to 2000, streamflow instrumentation at Coyote Creek has not changed (M. Jones, personal communication).

3 | METHODS

This study examined changes in daily average streamflow and its relationship to climate and forest structure and species composition in paired basins. Climate, vegetation, and streamflow have been measured for multiple decades at the Andrews Forest and Coyote Creek (see Supporting Information). Tree-level vegetation data were used to calculate basal area for all species, proportions of basal area for major species, and size class distributions.

Daily streamflow data for the period of record were used to calculate the change in streamflow by day of water year utilizing the method developed by Jones and Post (2004). R, the logarithm of the ratio of daily streamflow at the treated basin T and reference (control) basin C for year y and day d was calculated following Eberhardt and Thomas (1991) as

$$R_{y,d} = \ln\left(\frac{T_{y,d}}{C_{y,d}}\right). \tag{1}$$

The value M_{pd} was defined as the mean of R on day d for all years y in each period p.

The percent difference $\Delta_{p,d}$ between the treated: reference ratio of streamflow on day d in the post-treatment period p compared to $M_{p,d}$ in the pre-treatment period ($M_{p=0,d}$), was:

$$\Delta_{p,d} = 100\left[e^{(M_{p,d}-M_{0,d})}-1\right] \tag{2}$$

The 15-day smoothed percent change in daily streamflow, S, was calculated for all days d in each period p.

The smoothed daily percent difference S_{pd} was averaged for 5-year post-treatment periods and plotted as a function of day of the water year. S_{pd} also was summed by month and plotted as a function of time (year). Percent changes in daily streamflow were calculated for eight treated/reference basin pairs: COY 1/4, COY 2/4, COY 3/4, AND 1/2, AND 3/2, AND 6/8, AND 7/8, and AND 10/2. The significance of percent changes was assessed based on comparison with the 15-day smoothed values of the pre-treatment standard error of P_{pd}.

A daily soil water balance was created for AND 2 based on mean daily values of precipitation and discharge, daily evapotranspiration estimated from S_{pd} (Jones & Post, 2004), and mean daily snow water equivalent modeled in Perkins and Jones (2008). In addition, long-term trends in streamflow were calculated for each day of the water year from the beginning of the record to 1996, for AND 2, 8, and 9, following Hatcher and Jones (2013; see Supporting Information).

Flow percentiles were calculated for each gage record, and the numbers of days of flow below each percentile were tallied by water year. The difference in numbers of days below selected percentiles between the treated and reference basin for 1995 to 2005 was calculated and compared to summer discharge at the reference basin for 100% treated/reference pairs.

4 | RESULTS

The structure and composition of native mature and old-growth forest in reference basins varied, reflecting wildfire history, but was stable over the study period. Basal area ranged from 66 to 89 m^2/ha depending on the basin and the year (Table 2). Douglas-fir (*Pseudotsuga menziesii*) was the dominant species, representing 55 to more than 90% of basal area, with varying amounts of western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*) in AND 2 and AND 8, and California incense cedar (*Calocedrus decurrens*) and white fir (*Abies concolor*) in COY 4 (Table 2). Trees in AND 2 (N-facing) and AND 8 (upper elevation) were large, with weighted mean stem diameter of roughly 0.66 m. In contrast, trees were smaller on the low elevation, SW-facing, relatively hot, dry slopes of AND 9, and the mid-elevation COY 4 in southwest Oregon, with mean diameter of just over 0.3 m (Table 2). Stem density ranged from 87 stems per hectare at the N-facing AND 2 to over 400 stems per hectare at the SW-facing AND 9. Over a 25-year period, stem density and basal area were stable in AND 2, although there was a slight net loss of Douglas-fir and a gain of western hemlock (Table 2). The size-class distributions of Douglas-fir reveal moderate-severity historical fire in AND 2 and moderate to high-severity fire AND 8 in the mid-1800s, which produced cohorts of regenerating Douglas-fir (Figure 2).

TABLE 2 Vegetation characteristics of the study basins, sampled over the period 1981 to 2011

					Basal area								Stem density (stems per hectare)	
					(m^2/ha)	As %								
Watershed	N of plots	Plot size (m^2)	Year	Age	All	PSME	TSHE	THPL	ABCO	CADE	PILA	Other[a]	All	PSME
Treated patches														
AND 1	132	250	2007	40	33 ± 14	85	3	1	0	0	0	11	1,454	919
AND 3	61	250	2007	43	35 ± 12	80	11	2	0	0	0	7	1,857	621
AND 6	22	250	2008	34	35 ± 9	77	11	9	0	0	0	3	1,107	699
AND 7	24	250	2008	24	23 ± 10	70	9	4	0	0	0	17	900	551
AND 10	36	150	2010	35	27 ± 12	81	4	2	0	0	0	13	893	437
COY 1[be]	--[f]	--[f]	2011	35–200[g]	66	56	5	0	17	12	5	5	992	194
COY 2[c]	4	150	2006	35	31 ± 12	82	0	0	0	13	0	5	1,733	1,150
COY 3[c]	4	150	2006	35	45 ± 13	80	0	0	0	10	0	10	1,533	1,083
Reference														
AND 2	67	250	1981	150–475[d]	69 ± 29	70	24	2	0	0	0	4	262	67
	67	250	2006	175–500[d]	72 ± 29	65	29	2	0	0	0	4	438	87
AND 8	22	1,000	2003	175–500[d]	86 ± 24	64	26	9	0	0	0	2	580	144
	22	1,000	2009	175–500[d]	89 ± 24	64	26	9	0	0	0	2	565	139
AND 9	16	1,000	2003	175–500[d]	84 ± 25	92	4	0	0	0	0	4	630	434
	16	1,000	2009	175–500[d]	85 ± 25	92	5	0	0	0	0	3	602	417
COY 2[b]	--[f]	--[f]	2011	150–350[g]	89	61	0	0	10	17	11	1	1,169	172
COY 4[b]	--[f]	--[f]	2011	150–350[g]	66	55	5	0	18	11	5	6	975	183

Basal area is mean ± standard deviation. PSME = *Pseudotsuga menziesii* (Douglas-fir); TSHE = *Tsuga heterophylla* (western hemlock); THPL = *Thuja plicata* (western red cedar); ABCO = *Abies concolor* (white fir); CADE = *Calocedrus decurrens* (California incense cedar); PILA = *Pinus lambertiana* (sugar pine); -- = not available.

[a]Other (at Coyote Creek) includes *Arbutus menziesii* (madrone), *Pinus ponderosa* (ponderosa pine), and *Taxus brevifolia* (Pacific yew). Other (at the Andrews Forest) includes *Acer macrophyllum* (bigleaf maple), *Castanopsis chrysophylla* (giant chinquapin), and *Prunus emarginata* (bitter cherry).

[b]Based on 2011 stand exam data for matrix (not forest plantations) from Anderson et al., 2013.

[c]Source: Arthur, 2007.

[d]Multi-age stand with mixed-severity fire history.

[e]Coyote 1 was sampled in 2006 (Arthur, 2007) and 2011 (Anderson et al., 2013).

[f]Data from a forestry stand examination, not from plots, and no standard error is provided.

[g]Source: Rothacher, 1969.

Basal area and growth rates in the 34- to 43-year-old plantations in the treated basins are at the lower end of those reported for managed plantations in the region (Figure 3). Basal area at the most recent measurement period (2007 to 2010) ranged from 27 to 35 m^2/ha, or between one third and one half of the basal area in the corresponding reference basin (Table 2). Douglas-fir, which was planted in the treated basins, was the dominant species, representing more than 80% of basal area. Stem density was 5 to 10 times higher in plantations than matched reference basins and ranged from 533 to more than 1,700 stems per hectare (Table 2). Mean diameters in plantations were one third to one fifth of those in corresponding reference basins, except for COY 1, where the large mean stem diameter (31 cm) reflects the retention of 50% of the overstory from the shelterwood harvest (Tables 1 and 2). Trees were smallest in AND 7 (shelterwood harvest, plantation aged 34 years) and largest in 100% clearcut and burned basins AND 1 (plantation, aged 40 years) and COY 4 (plantation, aged 35 years). AND 10, which was clearcut but not burned, had a high number of small stems (plantation, aged 35 years; Tables 1 and 2; Figure 2). Adjusting for age, rates of basal area growth were similar in all the 100% clearcut basins. The unburned basin (AND 10) and the shelterwood harvest basin (AND 7) had slightly lower rates of growth in the third decade after harvest (AND 10) and a precommercial thin (12% basal area removal) at year 28 in AND 7, but rates were similar by 35 years (Figure 3).

The daily soil water balance for the reference basin (AND 2, Figure 4) reveals extremely low rates of evapotranspiration and soil moisture in old-growth forests during the summer (July through September). Evapotranspiration is limited by low temperature in winter and low soil moisture in summer.

Daily streamflow has not changed in reference basins (Figure 5). Runoff declined slightly during the periods of snowmelt, but these minor changes were significant only at AND 2 (Figure 5). Summer streamflow did not change over time.

Conversion of old-growth forest to Douglas-fir plantations, which reached 34 to 43 years of age by the end of the record analyzed here,

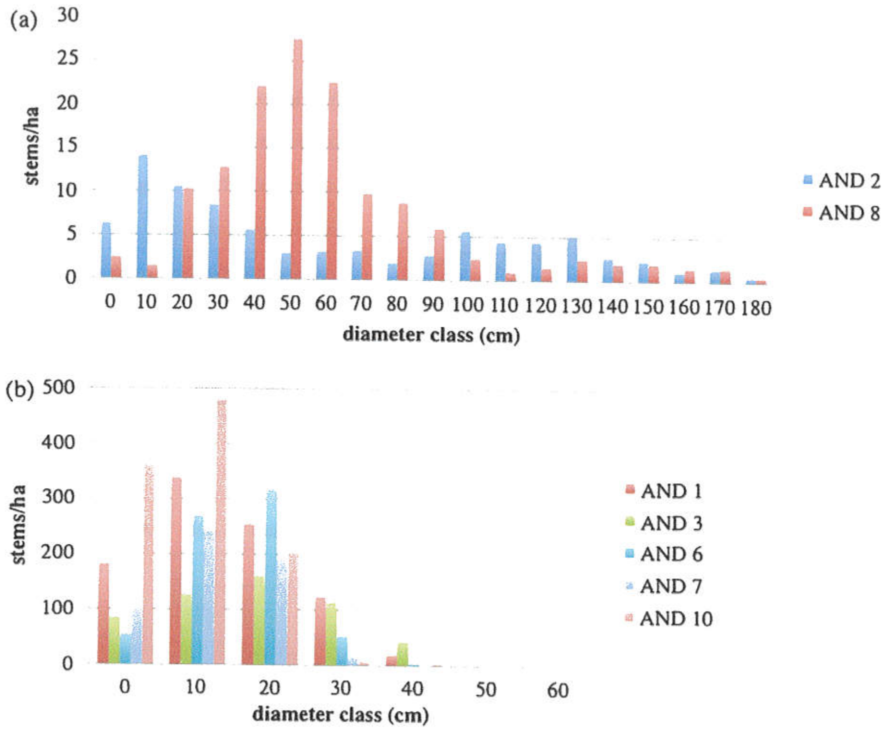

FIGURE 2 Size class distributions of Douglas-fir (*Pseudotsuga menziesii*, PSME) in plantations and reference basins in the Andrews Forest. (a) Reference basins used in this study: AND 2 (2006), AND 8 (2009). (b) Basins with young Douglas-fir plantations: AND 1 (aged 40 years, 2007), AND 3 (clearcut patches, aged 43 years, 2007), AND 6 (aged 34 years, 2008), AND 7 (aged 34 years, 2008), AND 10 (aged 35 years, 2010)

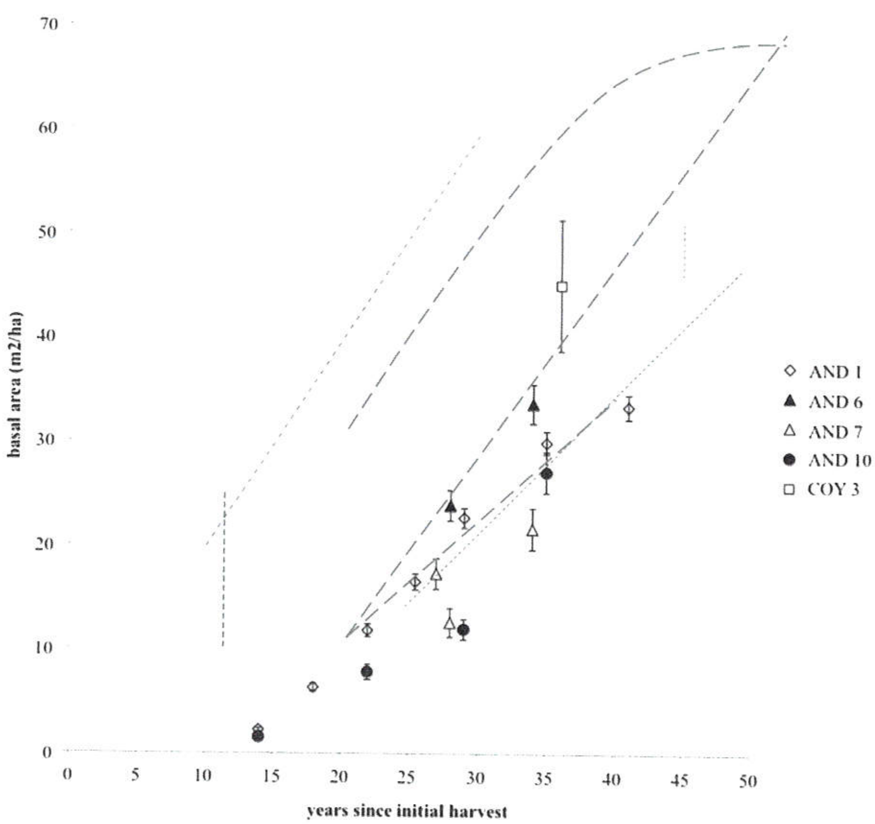

FIGURE 3 Basal area as a function of time since treatment in basins with forest plantations. Symbols are means ± standard error from numbers of plots shown in Table 2. The diagonal thick grey dashed lines are the basal area reported from control (unthinned) plots (upper line), heavily thinned plots (lower line), and lightly thinned plots (middle line) in the Hoskins levels-of-growing-stock (LOGS) installation (site II) in western Oregon (Marshall & Curtis, 2002). The diagonal thin grey dashed line indicates average annual basal area for Douglas-fir plantations on relatively high site productivity locations affected by various levels of infection from Swiss needle cast in the Oregon Coast Range (Maguire, Kanaskie, Voelker, Johnson, & Johnson, 2002). The thin grey diagonal dotted line indicates basal areas for experimental Douglas-fir plantations at low site productivity locations (site V) at Wind River (100 km north of the Andrews Forest, at a similar elevation to the experimental basins; Harrington & Reukema, 1983). The vertical grey dotted line is estimated Douglas-fir basal area from growth and yield models for 45-year-old stands (Marshall & Turnblom, 2005). The vertical grey dashed line is range of basal areas in stands of Douglas-fir, western hemlock, and mixtures (Amoroso & Turnblom, 2006)

had a major effect on summer streamflow. By the mid-1990s, average daily flow in summer (June through September) in basins with plantation forests had declined by roughly 50% relative to the reference basins with 150- to 500-year-old forests (Figure 6a). When plotted by time since harvest, summer streamflow deficits appeared when plantation forests reached 15 years of age (Figure 6b). The trend of declining summer streamflow was temporarily reversed in the late 1980s, especially at AND 1/2 and AND 6/8, after a severe freezing

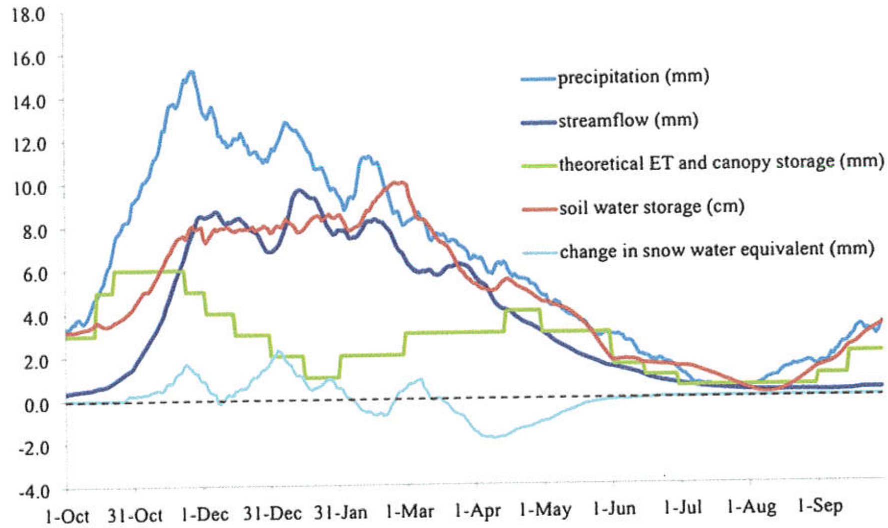

FIGURE 4 Water balance of mean daily values of precipitation (P), streamflow (Q), ET, snow water equivalent (N), and soil water storage (S) in AND 2, based on data from 1953 to 2003 water years, where $S = P - Q - ET - \Delta N$. Daily ET was estimated from the response of AND 1/2 to clearcutting calculated by Jones and Post (2004) and from summer sapflow measured in AND 2 by Moore et al., (2004). Snow water equivalent was based on average modeled daily values from Perkins and Jones (2008)

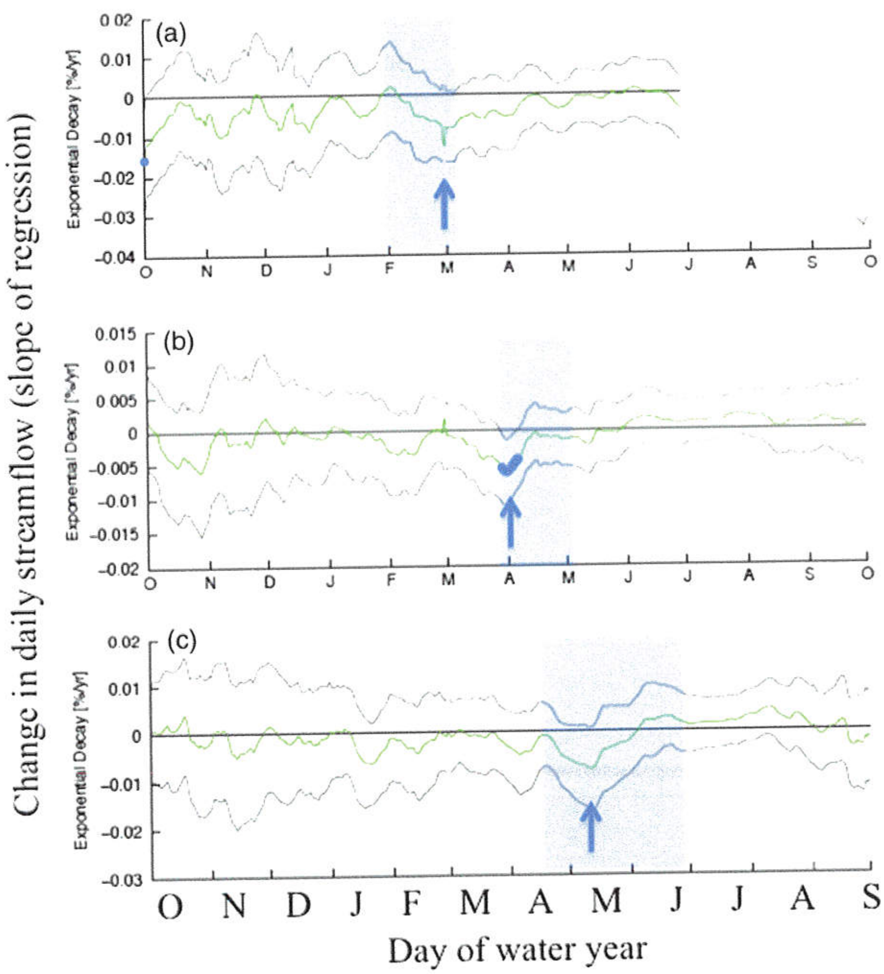

FIGURE 5 Streamflow change for period of record to 1996, by day of water year (October to September) for three reference basins: (a) AND 9 (400 to 700 m), (b) AND 2 (500 to 1,000 m), and (c) AND 8 (800 to 1,100 m). The green line is the trend in streamflow (positive or negative) on that day of the year, relative to the long-term mean streamflow on that day (indicated as zero). Black lines are the 95% confidence interval around the trend. Blue arrows indicate days of declining streamflow, and dark blue lines are days of significant declines in streamflow; declines are significant only at AND 2. Shaded boxes show the period of snowmelt from Perkins and Jones (2008). K. Moore, unpublished data

event in November of 1986. A pre-commercial thin (12% basal area) in AND 7 in 2001 did not slow the decline of summer streamflow.

When examined by day of year, forest harvest produced large streamflow increases from June through December in the first 10 years after harvest (Figure 7). Initial summer streamflow surpluses were lowest, and disappeared most quickly, in 50% thinned ("shelterwood") basins (AND 7, COY 1), and they were highest at the 100% clearcut basins (AND 1, 6, 10, COY 3; Figure 7). Conversion of mature and old forest to young plantations produced streamflow surpluses in winter and spring of 25% to 50%, which persisted virtually unchanged to the present in the Andrews Forest, but not at the drier, more southerly Coyote Creek (Figure 7).

By 20 to 25 years after 100% clearcutting, summer streamflow was lower in all plantation forests compared to reference basins

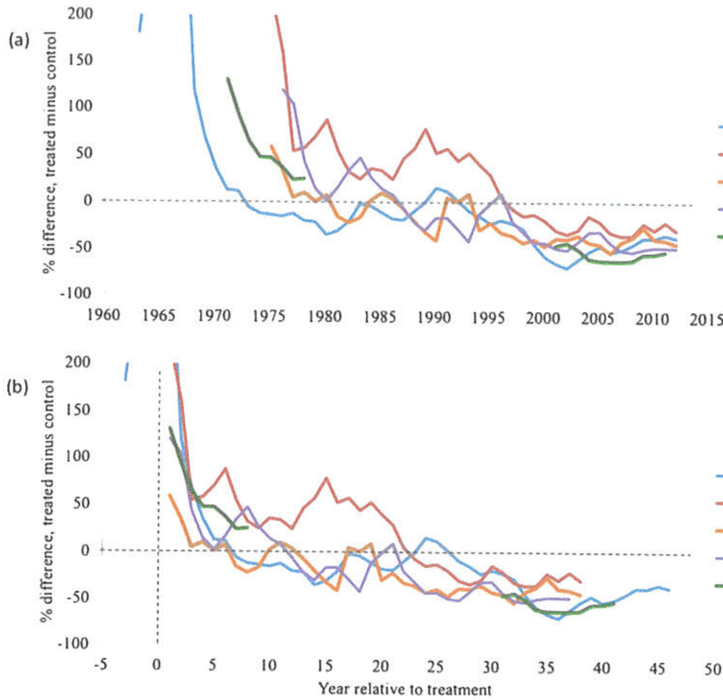

FIGURE 6 Trends in average daily streamflow (July through September) in basins with forest plantations as a percent of streamflow in the reference basin, for five basin pairs with 100% clearcut basins. (a) by year and (b) by time since treatment. Basin pair names include treated/reference. Percents are 3-year running means. Grey box is the mean ± the standard error of the treated-reference basin relationship from July to September during the pre-treatment period. Vertical axis maximum omits years when summer streamflow (July through September) at the treated basin exceeded 200% of pre-treatment level. Maximum percent increases (in unsmoothed data) were 683% at AND 1 (in 1966, fourth year of 1962-1966 clearcutting treatment); 328% at AND 6 (in 1975, one year after treatment); 90% at AND 7 (in 1974, year of treatment); 203% at AND 10 (in 1976, one year after treatment); and 149% at COY 3 (in 1971, year of treatment). Blue detached line shows initial increase when clearcutting (1962 to 1966) began in AND 1. Blue line shows apparent "hydrologic recovery" at AND 1 circa 1990 noted by Hicks et al. (1991); while red line shows increasing streamflow after 1986; both trends are attributable to an extreme freezing event that killed regenerating vegetation. Overall pattern shows no hydrologic recovery to pre-treatment conditions

(Figure 7a–e) and also in one 25% patch cut basin (Figure 7g). In 100% clearcut basins, summer streamflow deficits began by early July, and persisted until early October (AND 1, AND 7, Figure 7a,c), to the end of November (AND 6, AND 10, Figure 7b,d), or to the end of December (COY 3, Figure 7e). Deficits were largest in August and September, when streamflow from forest plantations was 50% lower than from reference basins. Summer deficits did not emerge over time in treatments involving shelterwood (50% thinned, COY 1) and very small openings (0.6- to 1.3-ha patch cuts, COY 2; Figure 7f,h). Relative to 50% thinning (shelterwood) and very small openings, intermediate-sized openings (8-ha patch cuts, AND 3) produced larger initial summer surpluses and persistent summer deficits. The largest openings (20- to 100-ha clearcuts) produced the largest summer surpluses and the largest, persistent summer deficits, which extended into the fall season (Figure 7a–d). Thinning of young forest (AND 7) did not counteract summer streamflow deficits.

Summer streamflow deficits occurred during the period of minimum flow, when soil moisture is most limiting (Figures 4 and 7). The duration of summer streamflow deficits (defined as the difference in the number of days below the first percentile in basins with plantations vs. reference basins) was greater during dry compared to wet summers, at low compared to high elevation, and at the more southerly Coyote Creek compared to the Andrews Forest (Figure 8). Forest plantations that were aged 25 to 35 years in 1995 to 2005 had as many as 100 more days with flow below the first percentile compared to the reference basin (Figure 8). Within a basin pair, the number of days of flow below the first percentile increased in dry relative to wet summers (Figure 8).

5 | DISCUSSION

This study showed that, relative to mature and old-growth forest dominated by Douglas-fir and western hemlock or mixed conifers, forest plantations of native Douglas-fir produced summer streamflow deficits within 15 years of plantation establishment, and these deficits have persisted and intensified in 50-year-old forest stands. Forest stands in the study basins, which are on public forest land, are representative of managed (including thinned) forest stands on private land in the region, in terms of basal area over time (Figure 3), age (10 to 50 years), clearcut size (20 ha), and average rotation age (50 years) (Lutz & Halpern, 2006; Briggs, 2007). There are no significant trends in annual or summer precipitation (Abatzoglou, Rupp, & Mote, 2014) or streamflow at reference basins over the study period. This finding has profound implications for understanding of the effects of land cover change, climate change, and forest management on water yield and timing in forest landscapes.

The size of canopy opening explained the magnitude and duration of initial summer streamflow surpluses and subsequent streamflow deficits, consistent with work on soil moisture dynamics of canopy gaps. In 1990, Gray, Spies, and Easter (2002) created experimental gaps in mature and old-growth forests in Oregon and Washington, including neighboring sites to the study basins, with gap sizes of 40 to 2,000 m^2 (tree height to gap size ratios of 0.2 to 1.0). The smallest gaps dried out faster during the summer than the largest gaps, with the highest moisture levels in the medium-sized gaps, which had less direct radiation and less vigorous vegetation than the largest gaps. In

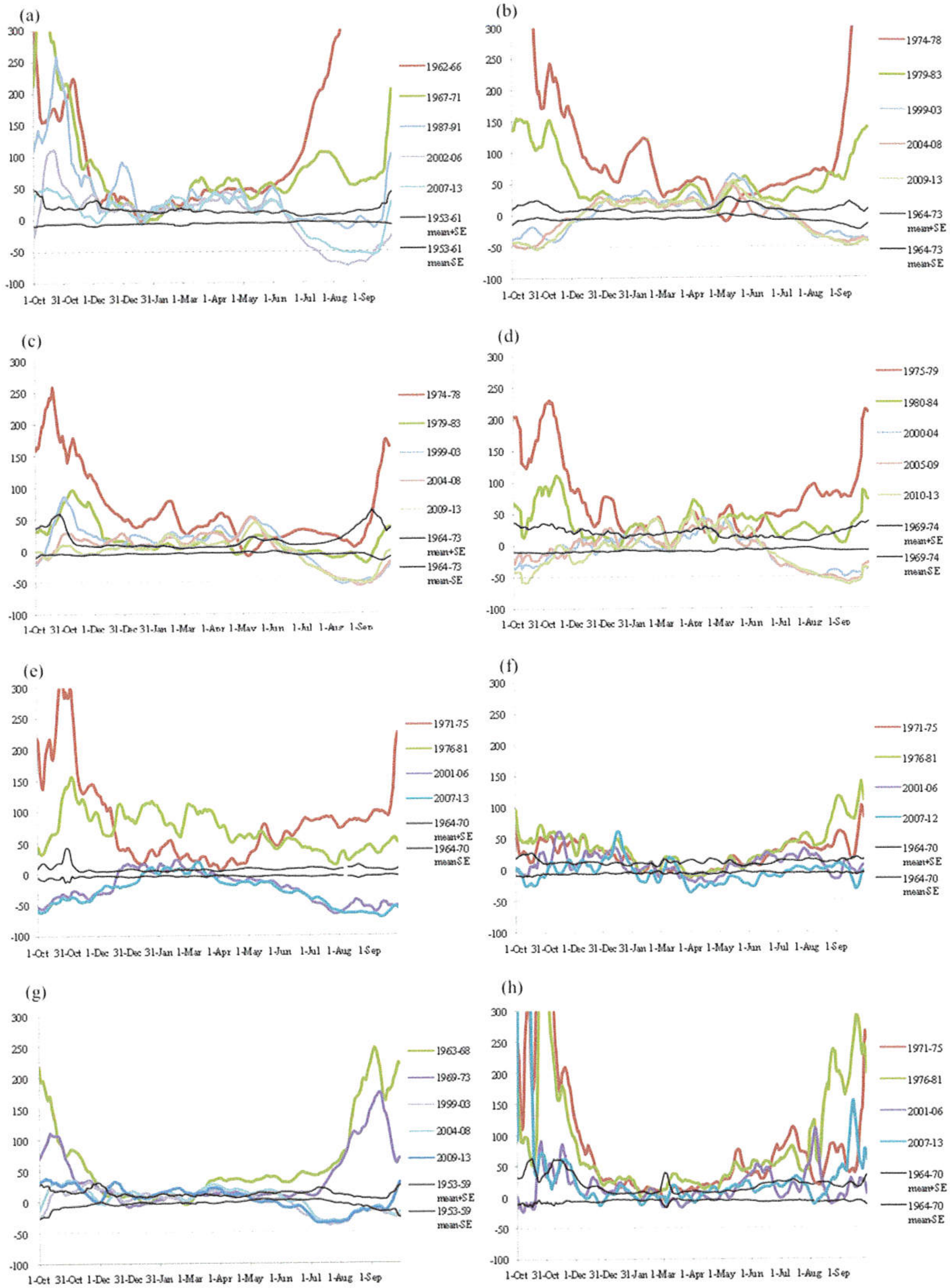

FIGURE 7 Percent change in streamflow by day of water year in 5-year periods after forest harvest and plantation establishment for eight pairs of basins. (a) AND 1 (100% clearcut 1962–66) versus AND 2 (reference), (b) AND 6 (100% clearcut 1974) versus AND 8 (reference), (c) AND 7 (50% cut 1974, remainder cut 1984) versus AND 8 (reference), (d) AND 10 (100% clearcut 1975) versus AND 2 (reference), (e) COY 3 (100% clearcut 1970) versus COY 4 (reference), (f) COY 1 (50% cut 1970) versus COY 4 (reference), (g) AND 3 (25% patch cut 1963) versus AND 2 (reference), (h) COY 2 (30% patch cut 1970) versus COY 4 (reference). Black lines represent the mean and standard error of the percent difference between the treated and reference basins during the pretreatment period. Dashed grey line is a 50% decline in streamflow at the treated basin relative to its relationship to the reference basin during the pretreatment period

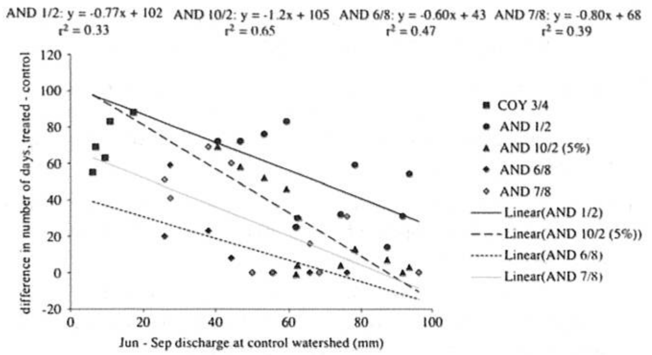

FIGURE 8 Difference in number of days in the first and fifth (AND 10/2) flow percentiles from 1995 to 2005, in basins with 25- to 40-year-old plantations relative to reference (old growth) basins. A value of 0 on the Y-axis indicates that the basin with forest plantation had the same number of days in the low flow percentile as the reference basin; a value of 80 indicates that the basin with forest plantation had 80 more days in the low flow percentile than the reference basin. Negative slopes of regression lines indicate that the duration of low streamflow increased in drier summers in the forest plantation, relative to the reference basin. The fifth percentile was used for AND 10/2 because only a few years had >0 day in the 1% category

late summer (September), volumetric soil moisture declined to 15% in references, 18% in small gaps, and 22% in each of the first 3 years after gap creation (Gray et al., 2002). Together, the paired basin and experimental gap results indicate that even-aged plantations in 8 ha or larger clearcuts are likely to develop summer streamflow deficits, and these deficits are unlikely to be substantially mitigated by dispersed thinning or small gap creation.

Relatively high rates of summer evapotranspiration by young (25 to 45 years old) Douglas-fir plantations relative to mature and old-growth forests apparently caused reduced summer streamflow in treated basins. Young Douglas-fir trees (in AND 1) had higher sapflow per unit sapwood area and greater sapwood area compared to old Douglas-fir trees (in AND 2; Moore, Bond, Jones, Phillips, & Meinzer, 2004). In summer, young Douglas-fir trees have higher rates of transpiration (sapflow) compared to old Douglas-fir trees, because their fast growth requires high sapwood area and because their needles appear to exercise less stomatal control when vapor pressure deficits are high. Leaf area is concentrated in a relatively narrow height range in the forest canopy of a forest plantation, whereas leaf area is distributed over a wide range of heights in a mature or old-growth conifer forest. In summer, these factors appear to contribute to higher daily transpiration rates by young conifers relative to mature or older conifers, producing pronounced reductions in streamflow during the afternoons of hot dry days (Bond et al., 2002). At sunset, transpiration ceases, and streamflow recovers. Hence, daily transpiration produces large diel variations in streamflow in AND 1 (plantation) relative to AND 2 (reference). Other factors, such as differences in tree species composition (Table 2), the presence of a hyporheic zone, or deciduous trees in the riparian zone of AND 1, may also contribute to differences in streamflow between these basins (Bond et al., 2002; Moore et al., 2004; Wondzell, Gooseff, & McGlynn, 2007).

Reduced summer streamflow has potentially significant effects on aquatic ecosystems. Summer streamflow deficits in headwater basins may be particularly detrimental to anadromous fish, including steelhead and salmon, by limiting habitat, exacerbating stream temperature warming, and potentially causing large-scale die-offs (Hicks et al., 1991; Arismendi, Johnson, Dunham, Haggerty, & Hockman-Wert, 2012; Arismendi, Safeeq, Johnson, Dunham, & Haggerty, 2013; Isaak, Wollrab, Horan, & Chandler, 2012). Summer streamflow deficits may also exacerbate trade-offs in water use between in-stream flows, irrigation, and municipal water use.

Reductions in summer streamflow in headwater basins with forest plantations may affect water yield in much larger basins. Much of the Pacific Northwest forest has experienced conversion of mature and old-growth forests to Douglas-fir plantations over the past century. Climate warming and associated loss of snowpack is expected to reduce summer streamflow in the region (e.g., Littell et al., 2010). Declining summer streamflows in the Columbia River basin may be attributed to climate change (Chang, Jung, Steele, & Gannett, 2012; Chang et al., 2013; Hatcher & Jones, 2013), but these declines may also be the result of cumulative forest change due to plantation establishment, fire suppression (Perry et al., 2011), and forest succession after wildfire and insect outbreaks, which kill old trees and promote growth of young forests (e.g., Biederman et al., 2015).

Air temperature has warmed slightly in the Pacific Northwest (0.6 to 0.8°C from 1901 to 2012; Abatzoglou et al., 2014), but water yields from mature and old-growth forests in reference basins have not changed over time. In the reference basins used in this study, we observed small changes in biomass and shifts in species dominance, consistent with changes expected as part of forest succession in mature and old-growth forests, but we did not observe large-scale mortality documented by van Mantgem et al. (2009).

This study demonstrates that plantations of native tree species produced summer streamflow deficits relative to mature and old-growth forest, consistent with prior studies in the U.S. Pacific Northwest (Jones & Post, 2004) and in mixed-deciduous forests in the eastern United States (Hornbeck, Martin, & Eagar, 1997). Research is needed to compare these effects to declining water yield from plantations of fast-growing non-native species in the southern hemisphere (Little et al., 2009; Little, Cuevas, Lara, Pino, & Schoenholtz, 2014; Scott, 2005; Farley et al., 2005). Despite summer streamflow deficits, young forest plantations in the Andrews Forest yield more water in winter, contributing to increased flooding (Harr & McCorison, 1979; Jones & Grant, 1996; Beschta, Pyles, Skaugset, & Surfleet, 2000; Jones, 2000; Jones & Perkins, 2010).

6 | CONCLUSIONS

Paired basin experiments are central to advancing long-term, integrated forest hydrology. Over the past half-century, many key paired-basin experiments (e.g., at U.S. Forest Service Experimental Forests and LTER sites such as Coweeta, Hubbard Brook, and Andrews) have evolved into headwater ecosystem studies, with detailed information about hydrology, climate, vegetation, biogeochemistry, and sediment export. These studies provide rigorous causal inferences about effects of changing vegetation on streamflow at successional time scales (multiple decades) of interest in basic ecology, applied forestry, and conservation. They permit researchers to distinguish forest management from climate change effects on streamflow. Paired-basin experiments are place-based science, integrate multiple disciplines of science and policy, and can dispel assumptions and conjectures such as equilibrium, common in hydrological modeling studies.

Long-term paired-basin studies extending over six decades revealed that the conversion of mature and old-growth conifer forests to plantations of native Douglas-fir produced persistent summer streamflow deficits of 50% relative to reference basins, in plantations aged 25 to 45 years. This result challenges the widespread assumption of rapid "hydrologic recovery" following forest disturbance. Widespread transformation of mature and old-growth forests may contribute to summer water yield declines over large basins and regions around the world, reducing stream habitats and sharpening conflict over uses of water.

Continued research is needed to examine how forest management influences streamflow deficits. Comparative studies, process studies, and modeling are needed to examine legacies of various past and present forestry treatments and effects of native versus non-native tree species on streamflow. In addition, long-term basin studies should be maintained, revived, and extended to a variety of forest types and forest ownerships, in order to discriminate effects of climate versus forest management on water yield and timing, which will be increasingly important in the future.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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