Home & Community Fire Resilience, Water Supply and Forest Protection

Lessons Learned from Recent Wildfires.

In 2020, Oregon experienced destructive wildfires that burned over 5,000 homes and business in communities across Oregon. In 2021, similar wind driven fires leveled communities in California and Colorado. In 2023, a wind driven fire burned Lahaina, Hawaii, and shortly thereafter a wind driven fire burned over 700 structures outside Spokane. These fires led to immense economic losses, and now the insurance industry has started exit new business in California, Oregon and other Western states.

Looking back, we see that these fires were driven by wind and amplified by drought. The Almeda fire in Talent and Phoenix was a wind-driven mass urban fire conflagration that ignited houses, which then became the fuel to ignite other houses. As Oregon State scientists have documented, we also witnessed increased severity of fires on intensely harvested industrial plantations, which are found on nearly 7 million acres across Oregon. (Zald & Dunn 2017, 2018). Over 70% of the Holiday Farm perimeter outside Eugene was timber plantations.

Around eighty percent of Oregon's drinking water supplies are found in forested watersheds. For some time, limited surface and groundwater have been a big challenge in drier parts of the state, and now Oregon is facing water challenges in Western Oregon that have led to inadequate supply and low flows in summer months. (e.g. Willamina, Dallas, Corbett, Nehalem, Rockaway Beach). Summer streamflow has been reduced by up to 50% by industrial logging practices in coastal watersheds according to studies by Oregon State University and independent experts. (Perry & Jones 2017, Segura et al 2019) A recent study by NASA found about one-third of forests across 80 drinking watersheds serving coastal cities have been cut during the last 20 years. (NASA 2023).

Solutions For Fire Safe Homes, Communities.

To prevent urban mass fire conflagrations, experts are telling us to prepare homes and communities to be ignition resistant before fire comes. (See On Fire, 2023 references to USFS Missoula Fire Lab, Insurance Institute for Business and Home Safety, Underwriter's Laboratory, National Fire Protection Association). In California, Nevada and Colorado, fire departments are scaling up home assessments and supporting homeowners to make the communities fire resistant. These actions help firefighters before fire comes, and they have been recognized by the insurance industry as essential actions to reduce risk. (e.g. WildfirePrepared.org). One local fire department in Oregon is expanding its efforts to direct assessment work. (e.g. Ashland).

In September 2023, a federally-commissioned group of over 50 wildfire experts issued On Fire, The Report of the Wildland Fire Mitigation and Management Commission and it strongly supported fire preparedness before fire comes. The commission recommended focused actions towards fire resilient communities, which are in the wheelhouse of state and local agencies to accomplish. In December 2023, a group of prominent experts underscored how we can protect homes and communities from fast-moving, destructive fires. They recommended funding local fire departments and counties, who are trusted by their local communities, to directly reach homeowners and vulnerable communities to help them participate in wildfire risk reduction programs (Gaither et al., 2011; Ojerio et al., 2010). The experts are telling us to expand and fund mitigation programs in communities and develop resources for communities at greatest risk and with limited capacity to improve wildfire resilience.

Industrial Increases Fire Risk, Decrease Water Supplies & Don't Pay Fair Share.

Forestland owners in Oregon have different goals and employ a variety of approaches towards management of their lands. Oregon has over 30 million acres of forests, 11 million acres of which is privately owned. Nearly 6.8 million acres of private land is managed for intensive harvest and high economic returns, the remainder is primarily managed for wildfire, water, privacy and aesthetics. While the Oregon Forest Practices Act limits harvest to some degree, large timber corporations continue to make substantial returns from short-rotation plantation forestry which negatively impacts water supplies and increase fire risk to neighboring communities.

In the 1990's, the Republican controlled legislature made a deal to eliminate substantial revenues from timber harvest. The big winners over the past 30 years were industrial timber corporations, the flip side is that this meant billions in disinvestment in communities across Oregon. (OPB, Oregonian, Pro Publica, Schick et al. 2020). These short rotation plantations also impose a big cost on Oregon as large clear cut openings have had a disproportionate negative impact on clean water supplies and have increased fire risk to adjacent communities. (Dunn and Zald 2017, 2018).

Currently Oregon taxes timber through the Harvest Tax system which must go through an industry approved process to determine rates and then a 3/5 majority approval by the legislature every other year. This cumbersome process for a small amount of money has resulted in very low taxes on industrial timber harvest, and huge underinvestment in rural communities. The referral process gives the legislature the best opportunity to accomplish pressing work and create a permanent and focused fund for wildfire preparedness and drinking water protection and restoration. A referral allows the legislature to present voters with a honed opportunity to address the wildfire and water challenges facing our state. Restoring the severance tax would provided a permanent fund for fire safe communities and protect drinking watersheds. The source of revenue could be internally balanced and fair, with larger owners who engage in intensive harvest paying a proportionally larger percentage.

Scientific References

Severe fire weather and intensive forest management increase fire severity in a multi-ownership landscape (Zald & Dunn 2018) https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1002/eap.1710 (Our findings suggest intensive plantation forestry characterized by young forests and spatially homogenized fuels…were significant drivers of wildfire severity.)

High wildfire severity risk seen in young plantation forests (Zald and Dunn, 2017) https://today.oregonstate.edu/news/high-wildfire-severity-risk-seen-young-plantation-forests (Private industrial forests are dominated by younger trees that have thinner bark and lower crown height, the researchers wrote. Both those characteristics are known to lead to increased fire effects)

Extreme Winds Alter Influence of Fuels and Topography on Megafire Burn Severity in Seasonal Temperate Rainforests under Record Fuel Aridity https://www.mdpi.com/2571-6255/5/2/41 ("[Management in] fuel rich forests should focus instead on increasing community preparedness, hardening infrastructure, promoting forests that are more buffered against high-severity fire, and preparing for fire suppression (when weather permits), in addition to other FireWise activities such as wildfire awareness and evacuation planning."

Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA https://andrewsforest.oregonstate.edu/publications/4981 (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…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.)

Long-term effects of forest harvesting on summer low flow deficits in the Coast Range of Oregon https://www.sciencedirect.com/science/article/abs/pii/S0022169420302092 (Segura et al. 2020) (Results of this study indicated that 40- to 50-yr rotations of Douglas-fir plantations can produce persistent, large summer low flow deficits.)

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ON FIRE: The Report of the Wildland Fire Mitigation and Management Commission https://www.usda.gov/sites/default/files/documents/wfmmc-final-report-09-2023.pdf

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NASA imagery shows scale, impact of logging in drinking watersheds on Oregon Coast https://www.opb.org/article/2023/09/19/oregon-coastal-watersheds-nasa-imagery/

How intense logging degraded water at a popular Oregon Coast town, Columbia Insight, https://columbiainsight.org/how-intense-logging-degraded-water-at-a-popular-oregon-coast-town/

After the smoke, an aerial view of the Beachie Creek and Holiday Farm burns https://www.youtube.com/watch?v=4H9vAGLWtBY (Oregonian)

Big money bought Oregon's forests. Small timber communities are paying the price. https://www.opb.org/news/article/oregon-investigation-timber-logging-forests-policy-taxes-spotted-owl/ (OPB, Oregonian, Pro Publica)

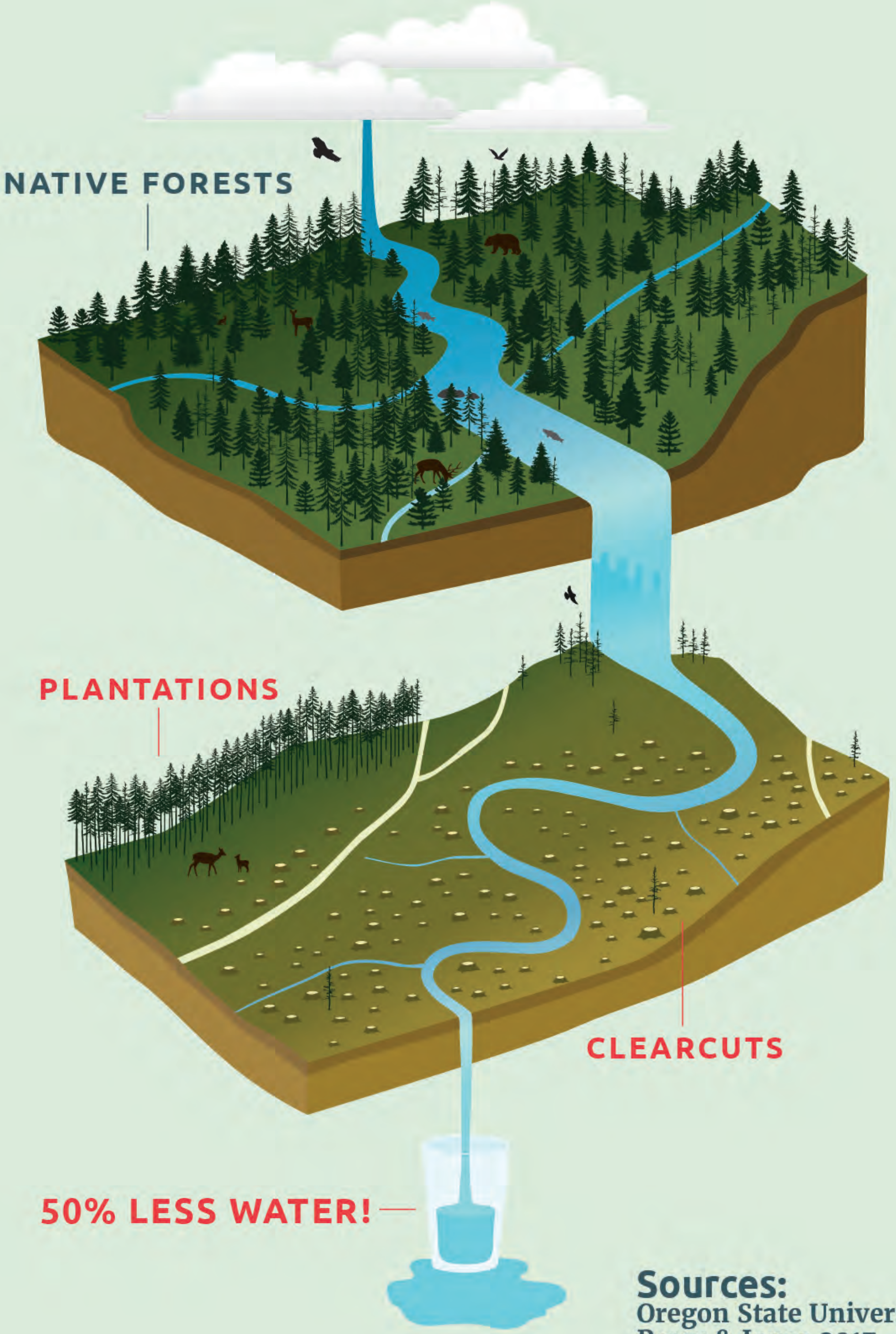
Study: Wildfires Burn More Severely On Private Timber Plantations Than Public Forests https://www.opb.org/news/article/wildfire-severity-private-public-forests/ (OPB)

Timber tax cuts cost Oregon towns billions. Then clear-cuts polluted their water and drove up its price (OPB, Oregonian, Pro Publica) https://www.opb.org/article/2020/12/31/oregon-logging-clear-cuts-drinking-water/

City of Corbett
Drinking Water Intake

WE CAN'T MAKE MORE WATER

CLEARCUT-PLANTATION FORESTRY REDUCES SUMMER STREAM FLOW BY FIFTY PERCENT COMPARED TO OLDER FOREST WATERSHEDS



FOREST WATERS

Sources:
Oregon State University
Perry & Jones 2017
Segura et al. 2019

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WILEY

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,

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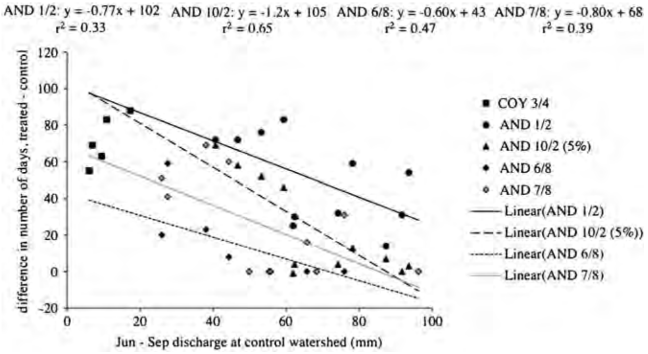

FIGURE 8 Difference in number of days in the first and fifth (AND 10/2) flow percentiles from 1995 to 2005, in basins with 25- to 40-year-old plantations relative to reference (old growth) basins. A value of 0 on the *Y*-axis indicates that the basin with forest plantation had the same number of days 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.

ACKNOWLEDGMENTS

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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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Alsea watershed study
Riparian buffer

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 clear-cutting 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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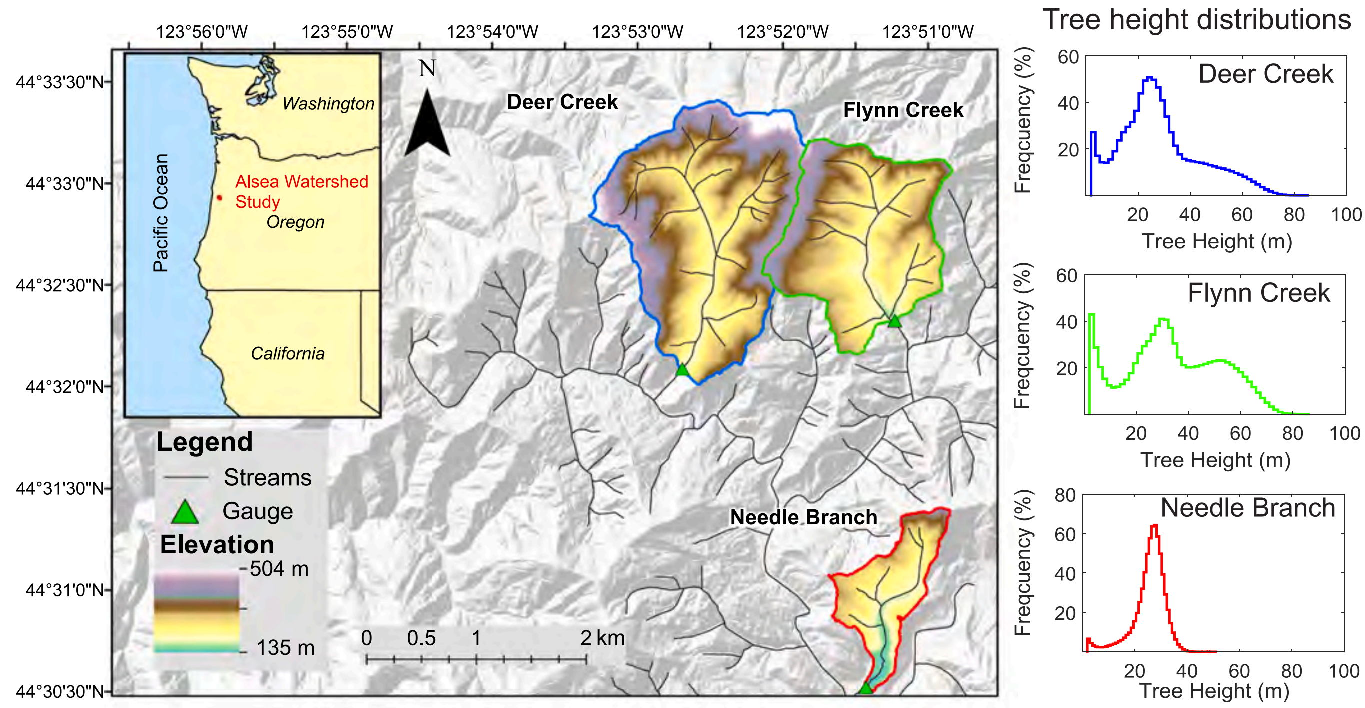

Fig. 1. Location and elevation of the Alsea Watershed Study and 2009 LiDAR derived tree height distribution in the three experimental watersheds of Deer Creek, Flynn Creek, and Needle Branch. Lidar acquisition occurred after the 2009 harvest in Needle Branch. Tree heights were obtained from the unharvested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

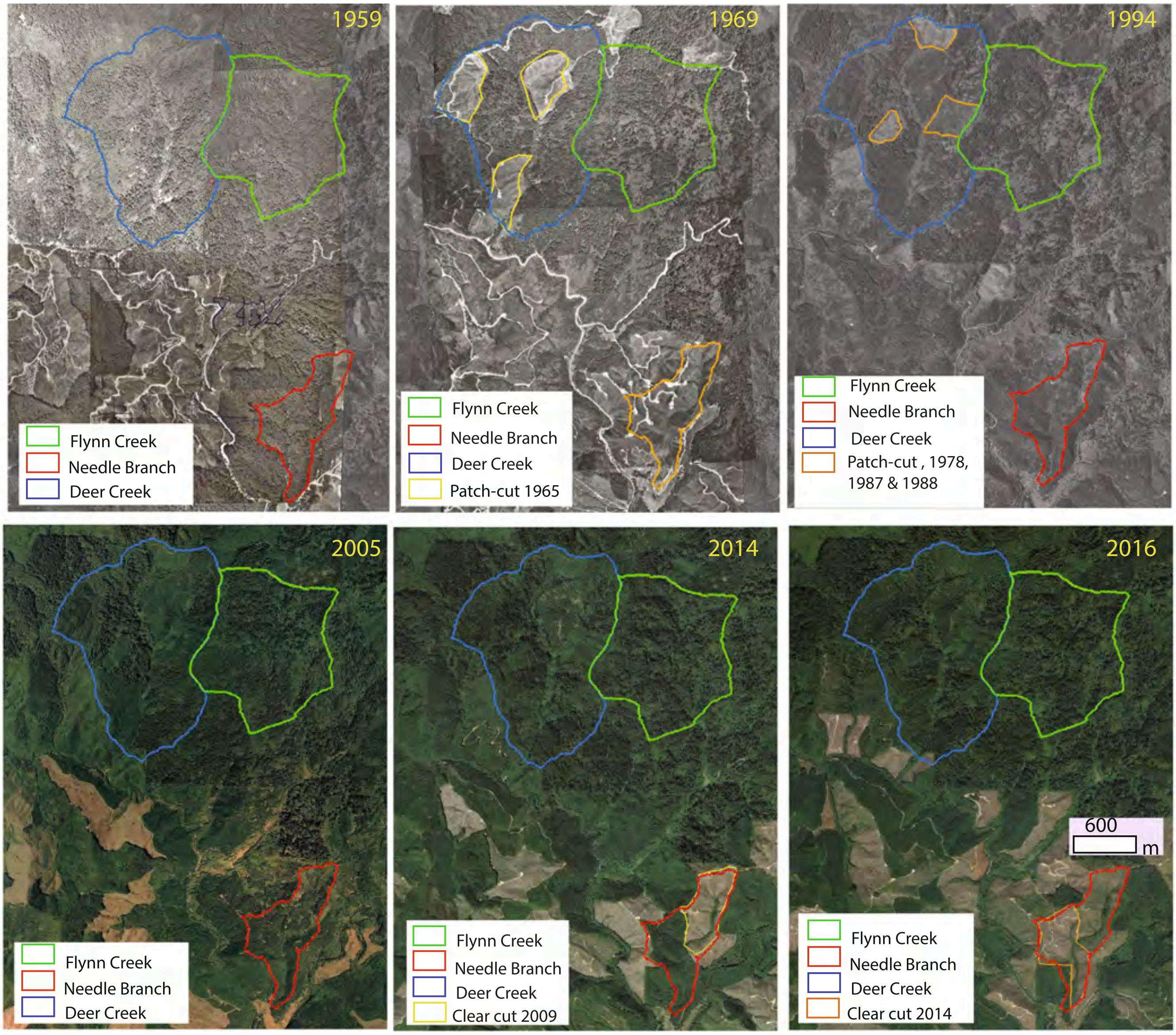

Fig. 2. Aerial view of the Alsea Watershed Study in 1959 (pre-first harvest entry), 1969 (post-first harvest entry), 1994 (post-thinning from 1978 to 1988 in Deer Creek), 2005 (pre-second harvest entry), 2014 (post-second harvest entry, Phase I), and 2016 (post-second harvest entry, Phase II).

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

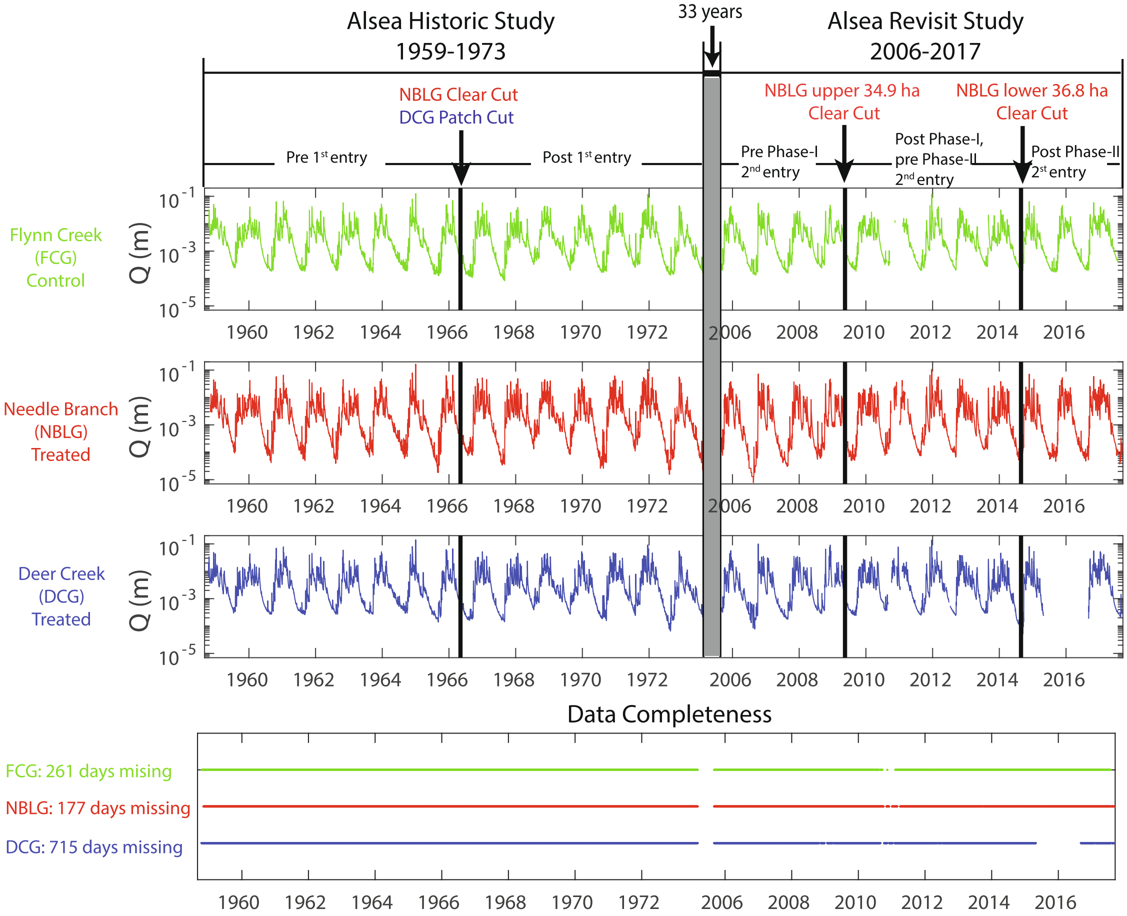

Fig. 3. Available discharge record in Flynn Creek Gauge (FCG), Needle Branch Gauge (NBLG), and Deer Creek Gauge (DCG) between water years 1959 and 2017. The historical harvest occurred in 1966 and the contemporary harvest occurred in 2009 (Phase I) and 2014 (Phase II).

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).

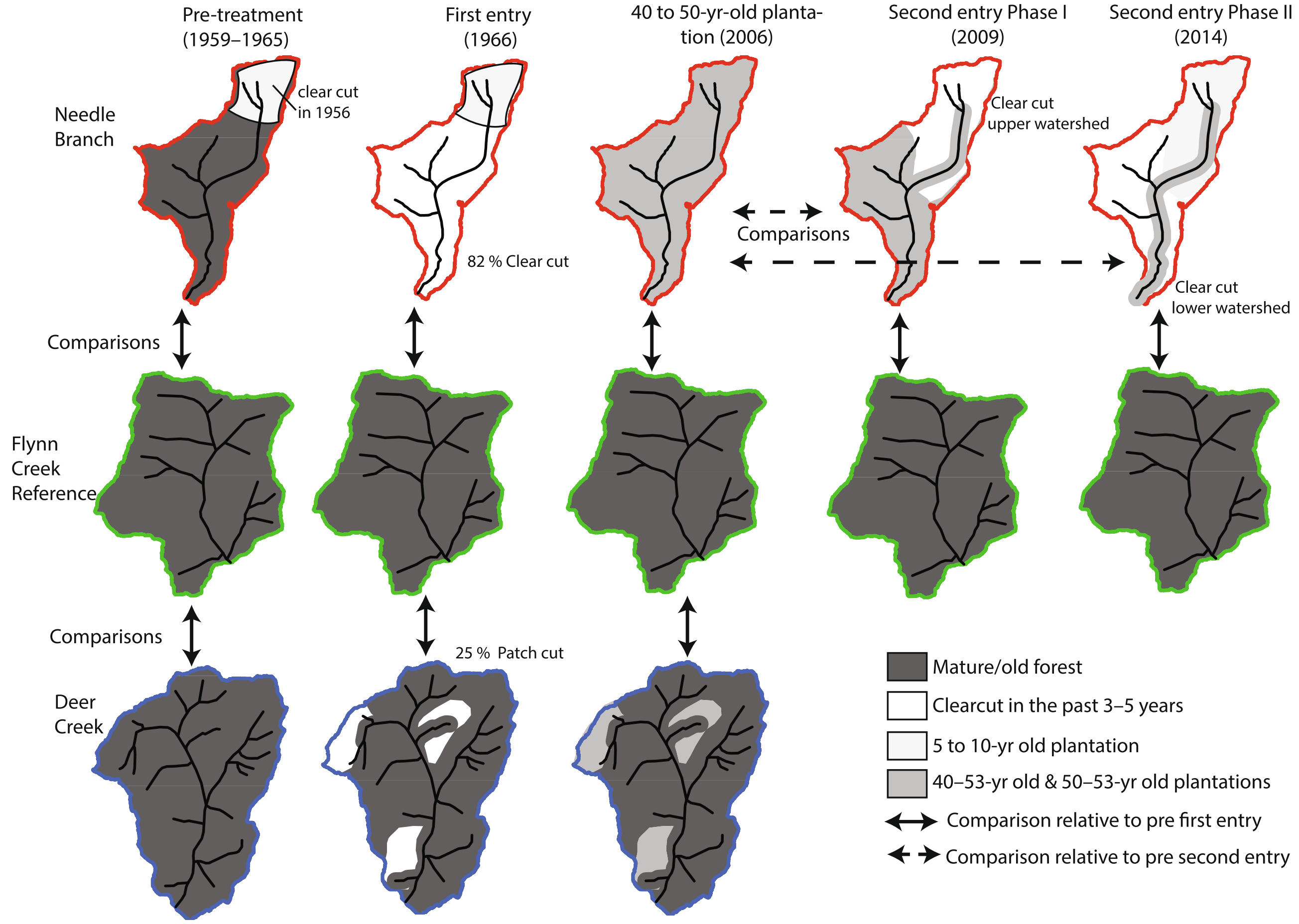

Fig. 4. A figure illustrating the different time periods and treatments used for comparisons of daily streamflow between the two harvested and replanted watersheds (Needle Branch, Deer Creek) relative to the reference watershed (Flynn Creek). The changes in streamflow associated with these comparisons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

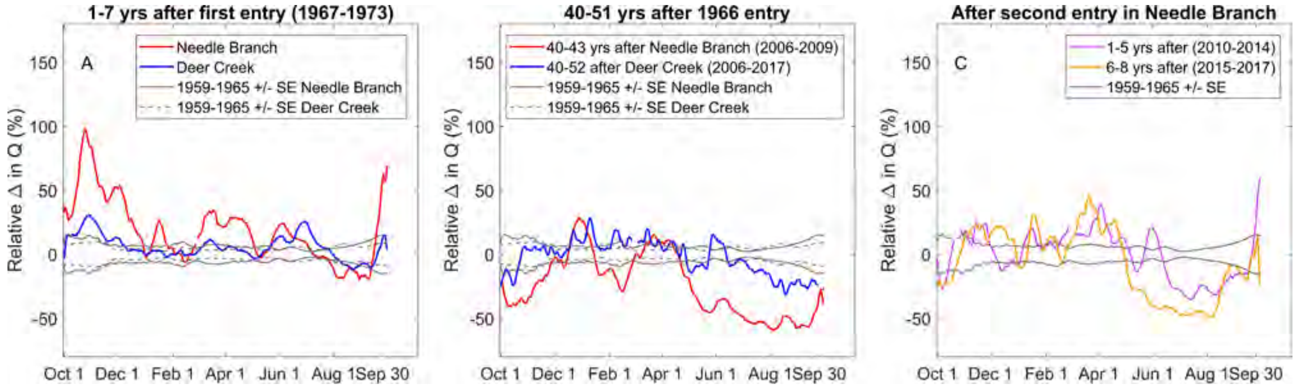

Fig. 5. Change in mean daily streamflow relative to the pre-harvest period (1959–1965) relationship with Flynn Creek (reference). Zero on the y-axis indicates no change in daily streamflow relative to the pre-treatment (1959–1965) relationship between the harvested watershed (Needle Branch, Deer Creek) 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 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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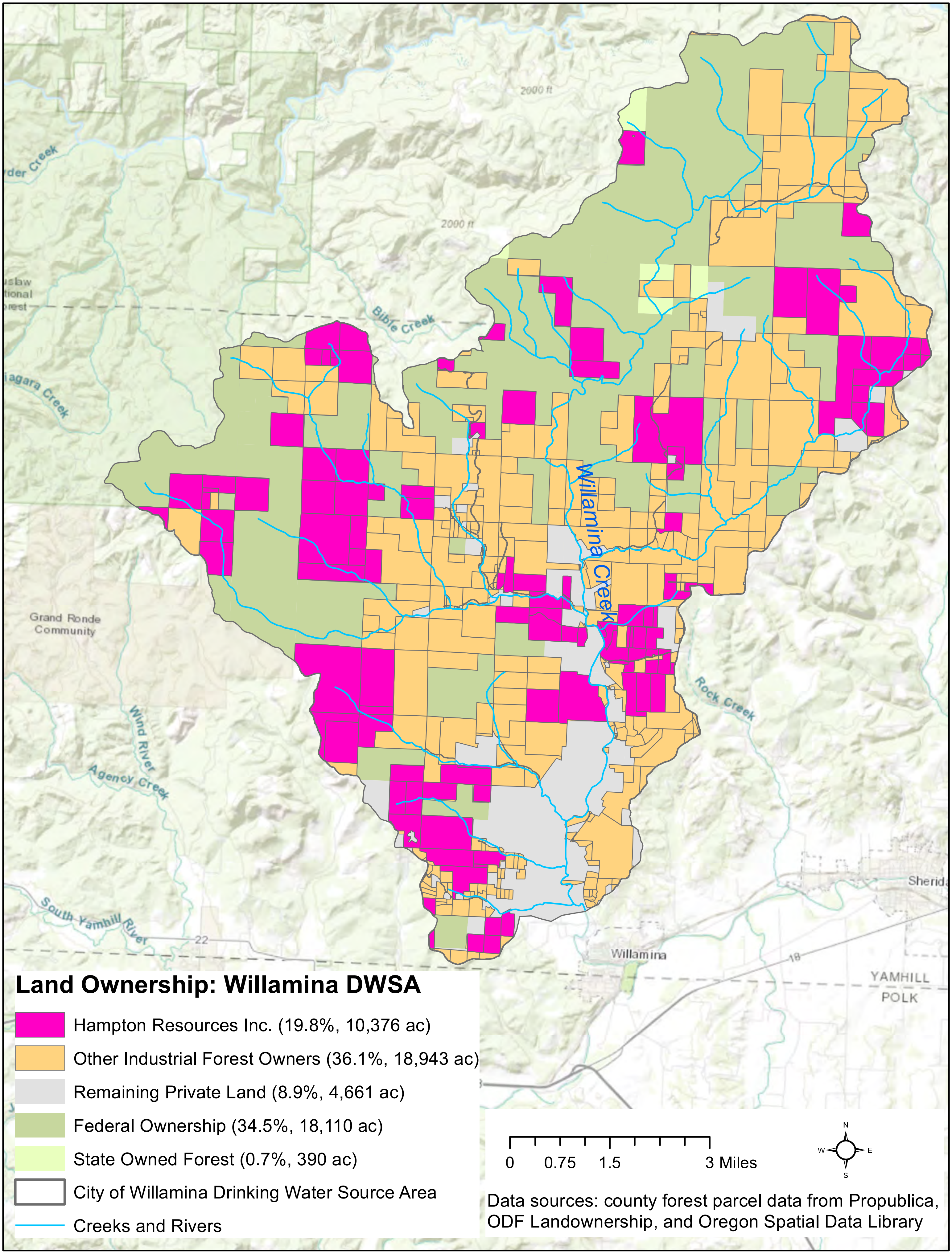


Land Ownership: Willamina DWSA

🟪 Hampton Resources Inc. (19.8%, 10,376 ac)

🟧 Other Industrial Forest Owners (36.1%, 18,943 ac)

⬜ Remaining Private Land (8.9%, 4,661 ac)

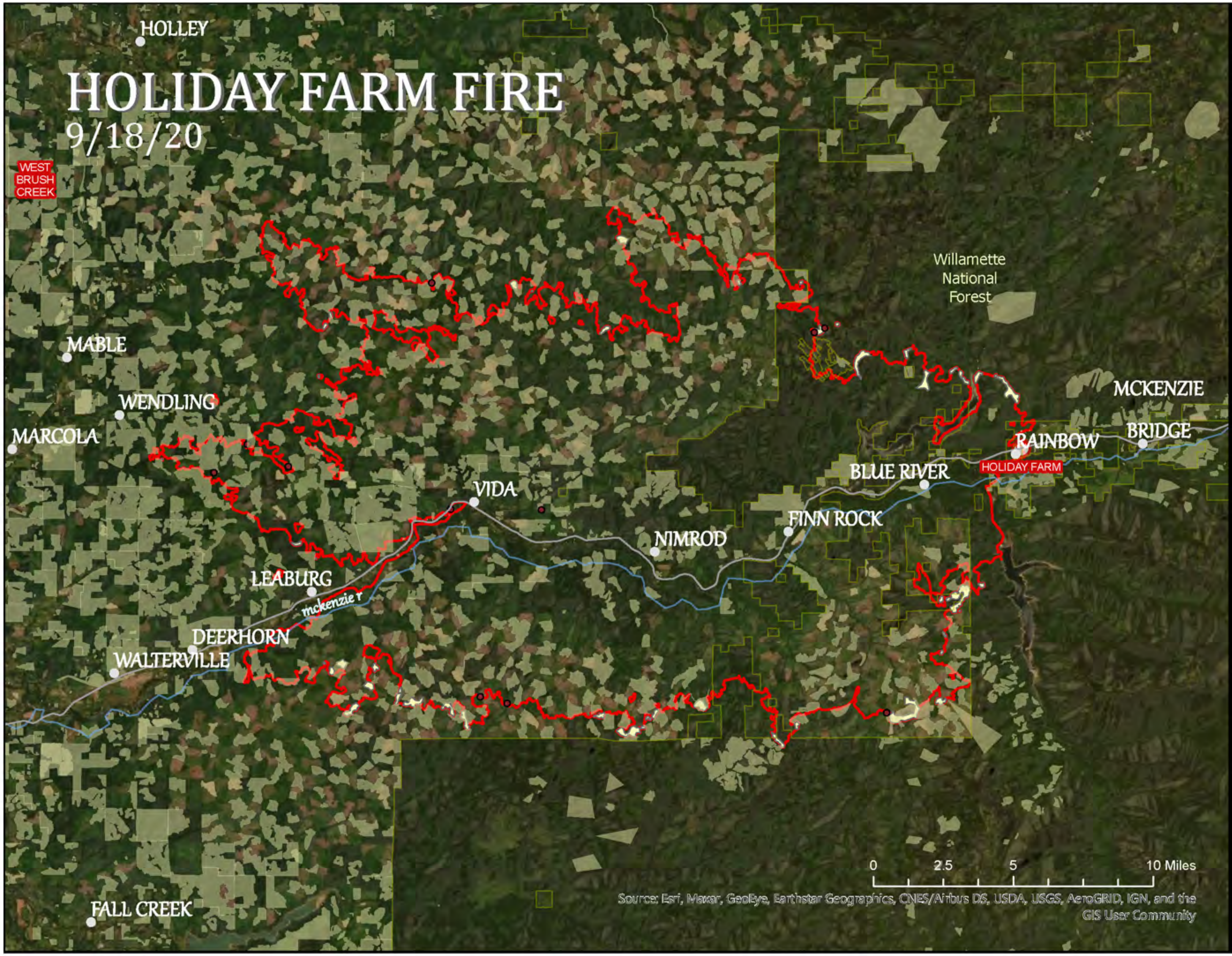
🟩 Federal Ownership (34.5%, 18,110 ac)

🟨 State Owned Forest (0.7%, 390 ac)

▭ City of Willamina Drinking Water Source Area

— Creeks and Rivers

Data sources: county forest parcel data from Propublica, ODF Landownership, and Oregon Spatial Data Library



HOLIDAY FARM FIRE

9/18/20

Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

FUSEE

FIREFIGHTERS UNITED FOR SAFETY, ETHICS & ECOLOGY

🟩 TIMBER PLANTATIONS

Sources: Oregon Dept. of Forestry, BLM Oregon, ESRI, VIIRS Imagery

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Severe fire weather and intensive forest management increase fire severity in a multi-ownership landscape

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Abstract. Many studies have examined how fuels, topography, climate, and fire weather influence fire severity. Less is known about how different forest management practices influence fire severity in multi-owner landscapes, despite costly and controversial suppression of wildfires that do not acknowledge ownership boundaries. In 2013, the Douglas Complex burned over 19,000 ha of Oregon & California Railroad (O&C) lands in Southwestern Oregon, USA. O&C lands are composed of a checkerboard of private industrial and federal forestland (Bureau of Land Management, BLM) with contrasting management objectives, providing a unique experimental landscape to understand how different management practices influence wildfire severity. Leveraging Landsat based estimates of fire severity (Relative differenced Normalized Burn Ratio, RdNBR) and geospatial data on fire progression, weather, topography, pre-fire forest conditions, and land ownership, we asked (1) what is the relative importance of different variables driving fire severity, and (2) is intensive plantation forestry associated with higher fire severity? Using Random Forest ensemble machine learning, we found daily fire weather was the most important predictor of fire severity, followed by stand age and ownership, followed by topographic features. Estimates of pre-fire forest biomass were not an important predictor of fire severity. Adjusting for all other predictor variables in a general least squares model incorporating spatial autocorrelation, mean predicted RdNBR was higher on private industrial forests (RdNBR 521.85 ± 18.67 [mean ± SE]) vs. BLM forests (398.87 ± 18.23) with a much greater proportion of older forests. Our findings suggest intensive plantation forestry characterized by young forests and spatially homogenized fuels, rather than pre-fire biomass, were significant drivers of wildfire severity. This has implications for perceptions of wildfire risk, shared fire management responsibilities, and developing fire resilience for multiple objectives in multi-owner landscapes.

Key words: fire severity; forest management; Landsat; multi-owner landscape; Oregon; plantation forestry; RdNBR.

Introduction

The wildfire environment has become increasingly complicated, due to the unanticipated consequences of historical forest management and fire exclusion (Weaver 1943, Hessburg et al. 2005, Fulé et al. 2009, Naficy et al. 2010, Merschel et al. 2014), an increasingly populated wildland urban interface (Haas et al. 2013), and a rapidly changing climate (Westerling and Bryant 2008, Littell et al. 2009, Jolly et al. 2015). These factors are resulting in more intense fire behavior and increasingly negative ecological and social consequences (Williams 2013, Stephens et al. 2014). Fuels reduction via mechanical thinning and prescribed burning have been the dominant land management response for mitigating these conditions (Agee and Skinner 2005, Stephens et al. 2012), although there is an increasing recognition of the need to manage wildfires more holistically to meet social and ecological objectives. (North et al. 2015a, b). However, overcoming these challenges is inhibited by numerous disagreements in the scientific literature regarding historical fire regimes and appropriate policies and management of contemporary fire-prone forests (Hurteau et al. 2008, Hanson et al. 2009, Spies et al. 2010, Campbell et al. 2012, Odion et al. 2014, Collins et al. 2015, Stevens et al. 2016). These factors and others have resulted in a nearly intractable socioecological problem (Fischer et al. 2016); one that is compounded by the fact that many fire-prone landscapes consist of multiple owners and administrative jurisdictions with varying and often conflicting land management objectives.

Developing and prioritizing landscape fire management activities (i.e., thinning, prescribed fire, wildland fire use, and fire suppression) across jurisdictional and ownership boundaries requires landscape-scale assessments of the factors driving fire severity (i.e., the fire behavior triangle of fuels, topography, and weather). Researchers have focused on the influence of bottom-up drivers such as topography (Dillon et al. 2011, Prichard and Kennedy 2014, Birch et al. 2015), and fuels via fuel reduction effects (Agee and Skinner 2005, Raymond and Peterson 2005, Safford et al. 2009, Prichard and Kennedy 2014, Ziegler et al. 2017), as well as the top-down influence of weather on fire severity (Birch et al. 2015, Estes et al. 2017). They have also focused more broadly on how fire severity varies with vegetation and forest type (Birch et al. 2015, Steel et al. 2015, Reilly et al. 2017) and climate (Miller et al. 2012, Abatzoglou et al. 2017). While there is substantial value in further describing how components of the fire behavior triangle influence fire severity, we believe there is a need to account for these known influences on fire behavior and effects to understand

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how different management regimes interact with these controlling factors, so appropriate landscape management strategies can be developed to support social-ecological resilience in fire-prone landscapes (Spies et al. 2014, Schoennagel et al. 2017).

Understanding the relationships between forest management regimes and fire severity is especially important in multi-owner landscapes, where wildfire governance systems concerned about short-term property loss and public safety can reinforce perceptions of wildfire risk and hazard, resulting in individual property owners being less likely to make management decisions that reduce long-term risk exposure (McCaffrey 2004, Fischer et al. 2016). This is particularly important in landscapes that include intensive plantation forestry, a common and rapidly expanding component of forest landscapes at regional, national, and global scales (Cohen et al. 1995, Landram 1996, Del Lungo et al. 2001, Rudel 2009, FAO 2010, Nahuelhual et al. 2012). Researchers have hypothesized that intensive forest management reduces fire behavior and effects (Hirsch et al. 2001, Rodríguez y Silva et al. 2014). However empirical results have been mixed, with evidence that intensive forest management can either reduce (Lyons-Tinsley and Peterson 2012, Prichard and Kennedy 2014) or increase fire severity (Odion et al. 2004, Thompson et al. 2007), and that reduced levels of forest legal protection (a proxy for more active management) have been associated with increased fire severity in the western U.S. (Bradley et al. 2016). These conflicting results further complicate the development of fire governance and management strategies for increasing social-ecological resilience in a rapidly changing fire environment.

The quality, spatial scale, and spatial correlation of explanatory data (i.e., weather, topography, and fuels) are major limitations to empirically understanding how forest management activities influence fire severity across landscapes. Regional studies of fire severity often rely on spatially coarse climatic data (Dillon et al. 2011, Miller et al. 2012, Cansler and McKenzie 2014, Kane et al. 2015, Harvey et al. 2016, Meigs et al. 2016, Reilly et al. 2017), rather than local fire weather that can be a significant driver of fire area and severity (Flannigan et al. 1988, Bradstock et al. 2010, Estes et al. 2017). This is in part because finer-scale fire weather variables are often incomplete across the large spatial and temporal domains of interest. Additionally, regional studies often occur in areas with large elevation relief resulting in strong climatic gradients, while more local studies often have less elevation relief and potentially weaker climatic gradients. Perhaps more importantly, the geographic distribution of different ownership types and management regimes can confound quantification of the drivers of fire severity. For example, high elevation forests in the Pacific Northwest region of the United States are largely unmanaged as National Parks and congressionally designated wilderness areas, compared to intensively managed forests at lower elevations, resulting in differences in topography, weather, climate, forest composition, productivity, and historical fire regimes between ownerships and management regimes. While landscape studies of fire severity and management activities have used a variety of statistical techniques to account for spatial correlation of both response and predictor variables (Thompson et al. 2007, Prichard and Kennedy 2014, Meigs et al. 2016), these techniques may not overcome fundamental differences in response and predictor variables between management and/or ownership types.

In this study, we examined the drivers of fire severity within one large (~20,000 ha) wildfire complex that burned within the Klamath Mountains, an ecoregion with a mild Mediterranean climate of hot dry summers and wet winters in southwestern Oregon, USA. The fire burned within a checkerboard landscape of federal and private industrial forestry ownership. This spatial pattern of contrasting ownership and management regimes provided a unique landscape experiment where we quantified the effects of management regimes after accounting for variation in well-known drivers of fire behavior and effects. Leveraging geospatial data on fire severity, fire progression, fire weather, topography, prefire forest conditions, and past management activities, we asked two questions: (1) What is the relative importance of different variables driving fire severity? And (2) is intensive plantation forestry associated with higher fire severity?

METHODS

Study site

In the summer of 2013, the Douglas Complex burned 19,760 ha of forestland in southwestern Oregon, USA (Fig. 1). Starting from multiple lightning ignitions, individual small fires coalesced into two large fires (Dads Creek and Rabbit Mountain) managed as the Douglas Complex.

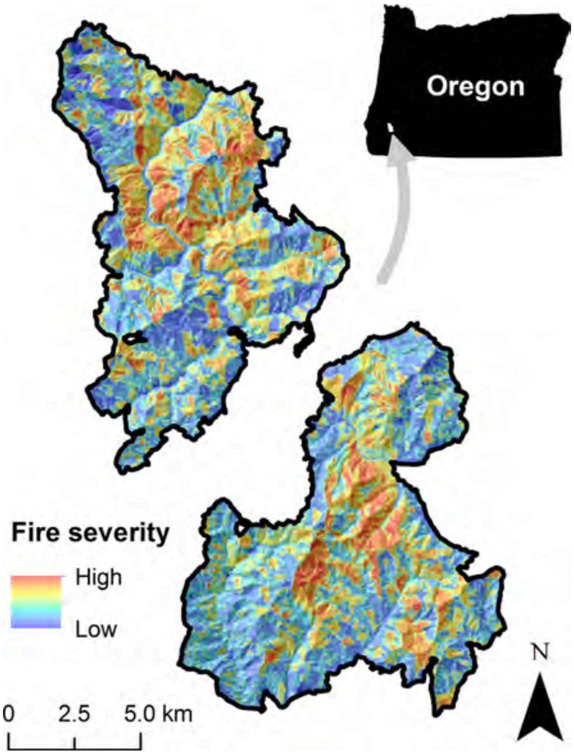

FIG. 1. Location of and fire severity within the Douglas Complex in Oregon, USA. Fire severity quantified using the Relative differenced Normalized Burn Ratio (RdNBR).

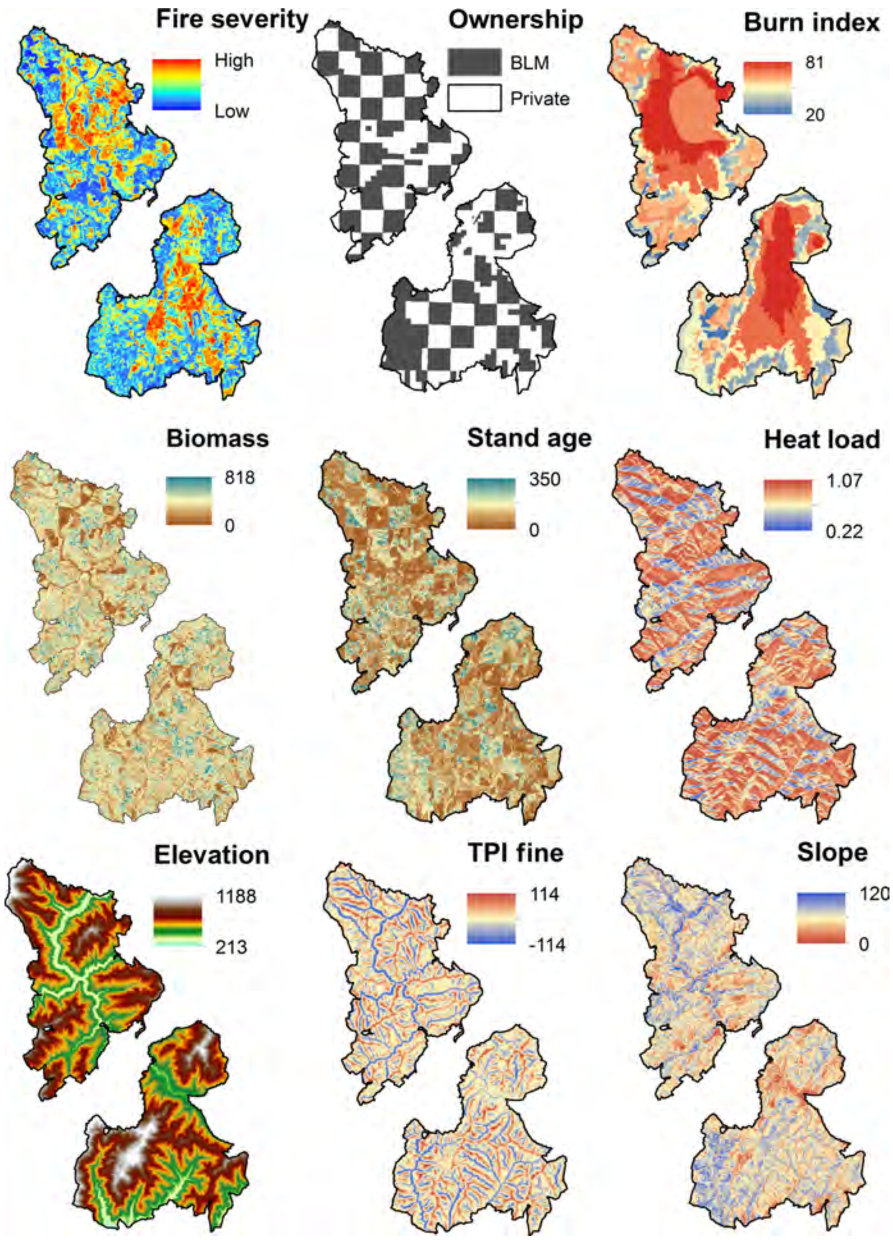

FIG. 2. Maps of response and predictor variables for Douglas Complex. TPI, topographic position index.

conifer stands with heavy dead fuel loads. Daily fire weather variables were then spatially extrapolated to the daily area burned based on daily fire progression geospatial data captured during the fire (GeoMAC 2013).

Forest ownership was derived from geospatial data representing fee land title and ownership in Oregon (Oregon Spatial Data Library 2015). We grouped ODF and BLM lands as a single ownership type, because ODF lands were a small component of the area burned and have management objectives closer to federal vs. private industrial forests (Spies et al. 2007). Pre-fire forest conditions were represented with 30-m rasters of live biomass (Mg/ha) and stand age, derived from a regional 2012 map of forest composition and structural attributes developed for the Northwest Forest Plan Monitoring Program (Ohmann et al. 2012, Davis et al. 2015). These maps were developed using the gradient nearest neighbor method (GNN), relating multivariate response variables of forest composition and structure attributes from approximately 17,000 federal forest inventory plots to gridded predictor variables (satellite imagery, topography, climate, etc.) using canonical correspondence analysis and nearest neighbor imputation (Ohmann and Gregory 2002). Biomass values are directly from the GNN maps, while we quantified forest age as a two-step process. First, we calculated pre-fire forest age in 2013 based on years since each pixel was disturbed in the Landsat time series (1985–2014) from a regional disturbance map generated for the Northwest Forest Plan Monitoring Program using the LandTrendr segmentation algorithm (Kennedy et al. 2010, Ohmann et al. 2012, Davis et al. 2015). Second, for pixels where no disturbance had occurred within the Landsat time series, we amended forest age derived from the Landsat time series using dominant and codominant tree age from the GNN maps.

Statistical analyses

All statistical analyses were conducted in the R statistical environment version 3.3.3 (R Development Core Team 2017). We sampled the burned landscape using a spatially constrained stratified random design, from which response and predictor variables were extracted for analysis. Sample points had to be at least 200 m apart to minimize short distance spatial autocorrelation of response and predictor variables. Our choice of minimum inter-plot distance to reduce spatial autocorrelation was confounded by the dominance of long distance spatial autocorrelation driven by large ownership patches, which would have greatly reduced sample size and potentially eliminated finer scale variability in the sample. For these reasons we based our 200 m minimum inter-plot distance in part on prior research (Kane et al. 2015), that found residual spatial autocorrelation in Random Forest models of fire severity in the Rim Fire of 2013 in the California Sierra Nevada was greatly diminished when inter-plot distances were at least 180 m apart. Additionally, point locations had to be at least 100 m away from ownership boundaries to minimize inter-ownership edge effects. Within these spatial constraints, sample points were located in a stratified random design, with the number of points proportional to area of ownership within the fire perimeter, resulting in 571 and 519 points located in BLM and private industrial forests, respectively. Mean response and predictor variables were extracted within a 90 × 90 m plot (e.g., 3 × 3 pixels) centered on each sample point location to minimize the effects of potential georeferencing errors across data layers and maintain a plot size comparable to the original inventory plots used as source data in GNN maps as recommended by Bell et al. (2015).

We observed high correlation between fire weather variables (mean absolute $r = 0.59$), likely due to their temporal autocorrelation during the fire event, which could result in multi-collinearity in statistical analyses. Therefore, we evaluated the relationships between each fire weather variable and daily mean fire severity, selecting a single fire weather variable as a predictor variable in subsequent analyses. We based our variable selection on visual relationships to daily RdNBR, variance explained in regressions of RdNBR and fire weather variables, and Akaike information criterion (AIC) scores of regressions of RdNBR and fire weather variables following Burnham and Anderson (2002).

The study's strength rests in part on the implicit assumption that the checkerboard spatial allocation of ownership types is a landscape scale experiment, where predictor variables directly modified by management activities (e.g., pre-fire biomass and forest age) are different between ownership types, but fire weather and topographic variables are not. We assessed this assumption by visualizing data distributions between ownerships using boxplots and violin plots, and testing if variables were different between ownership types using Mann–Whitney–Wilcoxon Tests.

To assess the relative importance and relationships between predictor variables and RdNBR, we used Random Forest (RF) supervised machine learning algorithm with the randomForest package (Liaw and Wiener 2002). As applied in this study, RF selected 1,500 bootstrap samples, each containing two-thirds of the sampled cells. For each sample, RF generated a regression tree, then randomly selected only one-third of the predictor variables and chose the best partition from among those variables. To assess the relative importance and relationships of predictor variables on RdNBR across the entire study area and within different ownerships, separate RF models were developed for all 1,090 sample plots across the entire burned area, as well as separately for plots on BLM and private industrial lands. For each of the three RF models, we calculated variable importance values for each predictor variable as the percent increase in the mean squared error (MSE) in the predicted data when values for that predictor were permuted and all other predictors were left unaltered. In addition to variable importance values, we determined which predictor variables should be retained in each RF model using multi-stage variable selection procedures (Genuer et al. 2010). We applied two-stage variable selection for interpretation to each RF model using the VSURF package (Genuer et al. 2016). Final RF models were then run including only the selected variables. Predictive power of the final RF models were assessed by calculating the variance explained, which is equivalent to the coefficient of determination (R^2) used with linear regressions to assess statistical model fit for a given dataset. Last, we visualized the relationships of individual predictor variables on RdNBR in the final RF models using partial dependency plots (Hastie et al. 2001).

Importance values in RF models are not the same as quantifying the fixed effects of predictor variables, nor is RF well suited to explicitly test hypotheses or quantify effects of predictor variables while accounting for other variables in a model. To test if ownership type increased RdNBR, we developed a generalized least squares (GLS) regression model with an exponential spherical spatial correlation structure using the nlme package (Pinheiro et al. 2017). The GLS regression used the distance between sample locations and the form of the correlation structure to derive a variance–covariance matrix, which was then used to solve a weighted OLS regression (Dormann et al. 2007). Using the same response and predictor data as in the RF model for the entire Douglas Complex, and a binary predictor variable for ownership type, we developed a GLS model from which we calculated the fixed effect of ownership on RdNBR. We then predicted the mean and standard error of RdNBR by ownership after accounting for the other predictor variables in the GLS model using the AICcmodavg package (Mazerolle 2017).

Results

Fire weather variables

Regression models of fire weather variables (except maximum temperature) described a significant proportion of the variance in daily mean RdNBR (Table 1; Appendix S1: Fig. S1). SC described the most variance in daily RdNBR, represent the total fuel load, but not the available surface and ladder fuels that have the potential to burn during a specific fire, and this is supported by the low importance of pre-fire biomass as a predictor of fire severity in our study. Furthermore, it is important to recognize that in addition to total surface and ladder fuels, the spatial continuity of these fuels strongly influences fire behavior (Rothermel 1972, Pimont et al. 2011). Fifth, while private industrial and BLM forests in our study area had very different forest conditions due to contrasting management regimes, ownership alone misses management activities (e.g., site preparation, stocking density, competing vegetation control, partial thinning, etc.) that can influence fuels and fire behavior. Sixth, while our spatial extrapolation of fire weather correlated well with daily fire severity and area burned, it did not account for topographic mediation of weather that can influence fine scale fire behavior, nor did it examine the underlying weather patterns such as temperature inversions that are common to the region and may play a key role in moderating burning index (Estes et al. 2017). Finally, we were unable to discern the effects of fire suppression activities and whether they varied by ownership, since incident documentation of suppression activities are generally not collected or maintained in a manner consistent with quantitative or geospatial statistical analyses (Dunn et al. 2017).

Management Implications

Although only one fire complex, the contrasting forest conditions resulting from different ownerships within the Douglas Complex are consistent with many mixed-ownership or mixed-use landscapes, such that we believe our results have implications across a much broader geographic area. First, it brings into question the conventional view that fire exclusion in older forests is the dominant driver of fire severity across landscapes. There is strong scientific agreement that fire suppression has increased the probability of high severity fire in many fire-prone landscapes (Miller et al. 2009, Calkin et al. 2015, Reilly et al. 2017), and thinning as well as the reintroduction of fire as an ecosystem process are critical to reducing fire severity and promoting ecosystem resilience and adaptive capacity (Agee and Skinner 2005, Raymond and Peterson 2005, Earles et al. 2014, Krofcheck et al. 2017). However, in the landscape we studied, intensive plantation forestry appears to have a greater impact on fire severity than decades of fire exclusion. Second, higher fire severity in plantations potentially flips the perceived risk and hazard in multi-owner landscapes, because higher severity fire on intensively managed private lands implies they are the greater source of risk than older forests on federal lands. These older forests likely now experience higher fire severity than historically due to decades of fire exclusion, yet in comparison to intensively managed plantations, the effects of decades of fire exclusion in older forests appear to be less important than increased severity in young intensively managed plantations on private industrial lands.

Furthermore, our findings suggest challenges and opportunities for managing intensive plantations in ways that reduce potential fire severity. Increasing the age (and therefore size) of trees and promoting spatial heterogeneity of stands and fuels is a likely means to reducing fire severity, as are fuel reduction treatments in plantations (Crecente-Campo et al. 2009, Kobziar et al. 2009, Reiner et al. 2009). The extent and spatial arrangement of fuel reduction treatments can be an important consideration in their efficacy at reducing fire severity at landscape scales (Finney et al. 2007, Krofcheck et al. 2017). However, optimal extent and landscape patterns of fuels reduction treatments can be hampered by a wide range of ecological, economic, and administrative constraints (Collins et al. 2010, North et al. 2015a, Barros et al. 2017). In the past, pre-commercial and commercial thinning of plantations (a potential fuel treatment) in the Pacific Northwest were common, economically beneficial management activities that improved tree growth rates and size, but these practices have become less common with improved reforestation success, alternative vegetation control techniques, and shorter harvest rotations (Talbert and Marshall 2005). This suggests there may be strong economic limitations to increased rotation ages and non-commercial thinning in young intensive plantation forests. More broadly, the development of large-scale forest management and conservation strategies can face legal and equitability challenges in multi-owner landscapes given existing laws constraining planning among private organizations (Thompson et al. 2004, 2006).

We believe two major questions arise from our findings that are important to fire management in multi-owner landscapes, especially those with contrasting management objectives. Plantations burned at higher severity, and this implies they are a higher source of risk to adjacent forest ownerships. However, a more explicit quantification of fire severity and susceptibility is needed to understand how risk is spatially transmitted across ownership types under a variety of environmental conditions. Second, we suggest the need for alternative management strategies in plantations to reduce fire severity at stand and landscape scales. However, the economic viability of such alternative management regimes remains poorly understood. Optimization models integrating spatial allocation of fuel treatments and fire behavior with economic models of forest harvest and operations could be used to determine if alternative management activities in plantations are economically viable. If alternative management activities are not economically viable, but wildfire risk reduction is an important objective on lands adjacent to industrial forestlands, strategic land purchases or transfers between ownership types may be required to achieve landscape level goals. This may be particularly important given the previously stated legal and equitability challenges in multi-owner landscapes. Regardless of the landscape-level objectives and constraints, it is clear that cooperation among stakeholders will be necessary in multi-ownership landscapes if wildfire risk reduction, timber harvesting, and conservation objectives remain dominant yet sometimes conflicting objectives for these landscapes.

Acknowledgments

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Check for updates

Higher incidence of high-severity fire in and near industrially managed forests

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The increasing prevalence of high-severity wildfire in forests in the US state of California is connected to past forest management, but uncertainty remains regarding the differential effects of land ownership on these trends. To determine whether differing forest management regimes, inferred from land ownership, influence high-severity fire incidence, we assembled and analyzed a large dataset of 154 wildfires that burned a combined area of more than 971,000 ha in California. We found that where fires occurred, the odds of high-severity fire on "private industrial" lands were 1.8 times greater than on "public" lands and 1.9 times greater than on "other" lands (that is, remaining lands classified as neither private industrial nor public). Moreover, high-severity fire incidence was greater in areas adjacent to private industrial land, indicating this trend extends across ownership boundaries. Overall, these results indicate that prevailing forest management practices on private industrial timberland may increase high-severity fire occurrence, underscoring the need for cross-boundary cooperation to protect ecological and social systems.

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The increased incidence of high-severity wildfires in the state of California and western US forests over the past several decades threatens both ecological and social systems (Stevens *et al*. 2017; Steel *et al*. 2018; Hessburg *et al*. 2021). The complete or near-complete mortality of dominant vegetation associated with high-severity fire effects, and the unprecedented scale of these effects, is particularly concerning in certain forests – including many in California – where tree species lack direct mechanisms for recovery or regeneration from large, severe fires (Shive *et al*. 2018). These forests are highly fire prone and adapted to withstand low–moderate severity fires, which primarily spread on the forest floor but recover slowly (decades to centuries) from extensive high-severity crown fire (Coop *et al*. 2020). Trends in high-severity fire are associated with the broader pattern of increasingly extreme wildfire events that has resulted in the loss of human life, extensive property damage, carbon emissions, and long-lasting disruptions to ecosystem services and the communities that rely on them (Stephens *et al*. 2014; Stenzel *et al*. 2019). The effects of these fires on forest ecology are long-lasting and can facilitate conversion to non-forest ecosystem types, which has major negative implications for carbon storage and wildlife habitat (Coop *et al*. 2020).

There are discussions in the scientific, management, and political arenas about the causes of increased extreme fire effects, a conflict that has played out in forums ranging from presidential statements to high-profile court cases (Dixon 2018), scientific journals (Peery *et al*. 2019; Hagmann *et al*. 2021), and traditional news media. Much of this discussion focuses on the role of forest management or lack thereof in contributing to more extensive high-severity effects.

Disputes about the role of forest management in driving extreme wildfire effects frequently center on the differing management practices of industrial timber companies and public land agencies (Schwartz *et al*. 2020). Typically, industrial timber companies aim to maximize sustainable wood production while minimizing costs; consequently, intensive management practices such as plantation forestry, a highly efficient method of timber production (Sedjo 1999), are frequently applied. In contrast, forest management by public agencies in California, such as the National Park Service (NPS), the Bureau of Land Management (BLM), and the US Forest Service (USFS), tends to have a substantially smaller impact, as measured by standing biomass and removals (Stewart *et al*. 2016). This is largely due to the diverse set of objectives across public forests, ranging from resource conservation to recreation, lower consensus on management goals, and increased litigation and public scrutiny (Collins *et al*. 2017).

There is considerable scientific disagreement concerning how these different forest management approaches affect fire severity. On public lands, the combination of aggressive fire suppression with low rates of both restoration thinning and fuel treatments has resulted in dense stands with high fuel loads that contribute to extreme fire behavior (Starrs *et al*. 2018). Meanwhile, under intensive plantation management, the homogenous stand structure and high fuel continuity common in even-aged plantations can foster rapid fire spread (Zald and Dunn 2018; Koontz *et al*. 2020). The complex and intermixed pattern of ownership boundaries in the western US further complicates this debate (Zald and Dunn 2018). Given the "contagious" nature of wildfire, it might be expected

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that issues of adjacency, wherein the heightened incidence of high-severity effects associated with a given management practice spills over onto nearby land of differing ownership types, receive greater attention.

Empirical studies of the relationship between ownership and fire severity are limited and conflicting. Several have demonstrated reduced fire severity and area burned in industrially managed forests (Lyons-Tinsley and Peterson 2012; Starrs *et al.* 2018), whereas others have reported increased severity (Zald and Dunn 2018). Most of these studies examined only a single fire event, with very little work done at larger geographic scales on cross-boundary risk associated with ownership type or management approach (but see Downing *et al.* 2022). Here, our goal was to quantify the impact of land ownership on the incidence of high-severity fire, conditional on fire occurrence, through large-scale analyses of wildfires in California. We also examined whether ownership effects on high-severity fire are vectored across ownership boundaries, and we compared these outcomes to the effects of other important topographic, climatic, and meteorological drivers of fire severity.

Methods

Study area

We analyzed 154 wildfires that burned a combined area exceeding 971,000 ha in California from 1985 to 2019 (Figure 1a; WebTable 1). All fires occurred in predominantly yellow pine (ponderosa pine [*Pinus ponderosa*] and Jeffrey pine [*Pinus jeffreyi*]) and mixed-conifer (white fir [*Abies concolor*], Douglas-fir [*Pseudotsuga menziesii*], incense-cedar [*Calocedrus decurrens*], ponderosa pine, sugar pine [*Pinus lambertiana*], and black oak [*Quercus kelloggii*]) forests. We refer to these forest types collectively using the acronym YPMC (that is, yellow pine and mixed-conifer). Historically, YPMC forests were characterized by high-frequency, low-to-moderate-severity fire regimes until the forced cessation of Indigenous burning practices in the 19th century and a policy of fire suppression was adopted in the early 20th century (Anderson 2013; Stephens *et al.* 2014). We selected all fires from the California interagency fire perimeter database (https://frap.fire.ca.gov/frap-projects/fire-perimeters) that contained both private industrial and public lands in YPMC forests with at least 16.2 burned ha (40 acres) in each

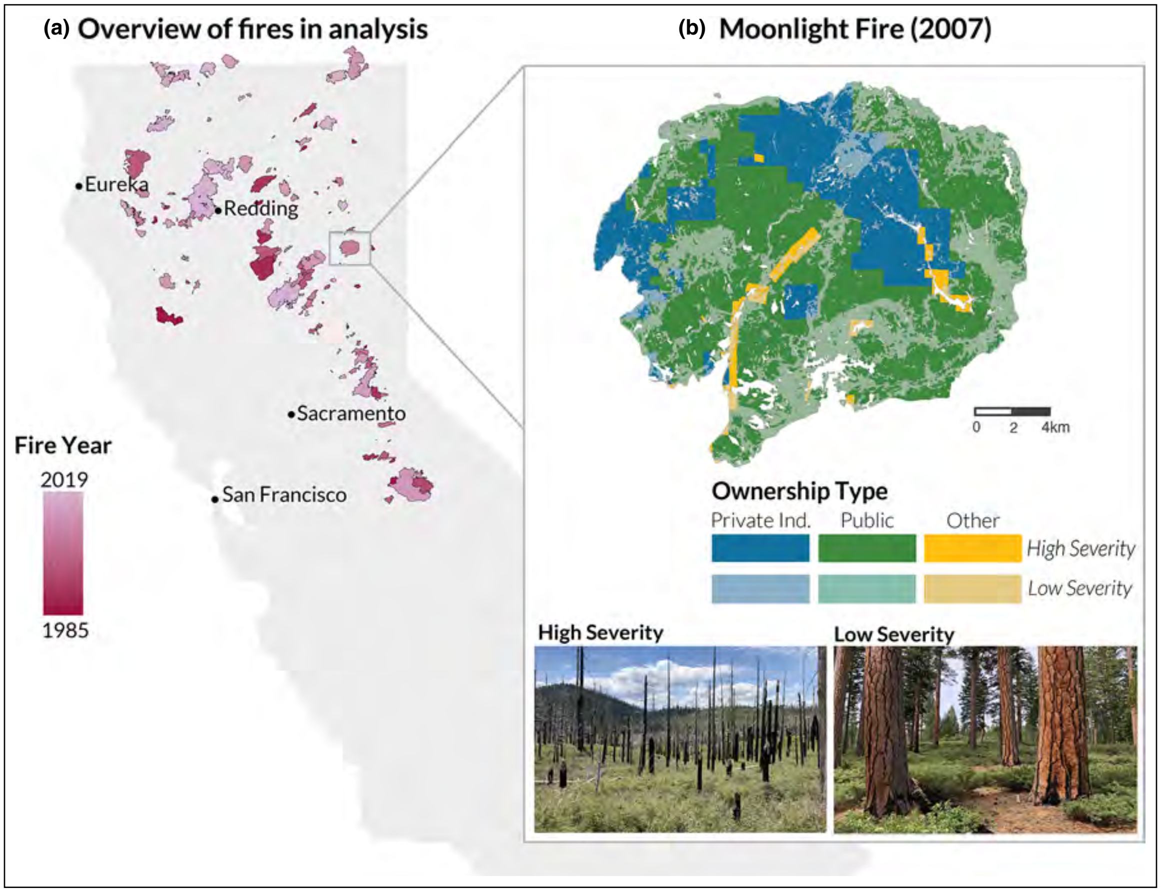

Figure 1. (a) Map of northern California, with the location of the 154 fires analyzed in the study. The year in which each fire burned is denoted by color, with lighter colors representing more recent fires. (b) Example of the ownership and severity patterns for one specific fire, the Moonlight Fire. Ownership is denoted by the three colors, with darker shades of each color representing areas that burned at high severity. Images were taken on public land (US Forest Service) within the Moonlight Fire perimeter in two locations, one that burned at high severity and another that burned at low severity, and depict the state of recovery 10 years after the fire; note high shrub density and lack of conifer regeneration in the high-severity location.

The lower probability of high-severity fire occurrence on public forest lands should not be interpreted as a tacit endorsement of public agencies' dominant management practices. Concerning increases in high-severity fire incidence are prevalent on lands across California, regardless of ownership type (Stephens *et al.* 2014; Stevens *et al.* 2017; Steel *et al.* 2018). The relatively better performance of public land is not evidence that forest management there is combatting this trend. Regardless of ownership type, scientific evidence suggests that massive increases in prescribed fire, managed wildfire for resource benefit, and restoration thinning are necessary to mitigate fire severity across the state (LHC 2018).

We chose to analyze high-severity fire specifically because of its severe ecological and economic consequences, but previous studies have identified opposite ownership-related trends when considering other important dimensions of fire regimes, including ignitions, patch size and complexity, and area burned (eg Starrs *et al.* 2018). This indicates that the role of ownership in the more general pattern of increasingly extreme wildfire events is nuanced. For example, differences in post-fire outcomes are worth noting; more active management on private industrial land often results in more successful reforestation post-fire (Stephens *et al.* 2020). Additional research is needed to fully evaluate the effect of ownership on wildfire patterns throughout California forests.

Several other limitations exist. For one, CBI, while predictive of on-the-ground fire effects (Miller *et al.* 2009; Lydersen *et al.* 2016), is an indirect measure of fire severity. Because it is derived from satellite imagery, CBI is not always reliable for distinguishing between young stands that burned at high severity and old stands that burned at high severity – outcomes that are distinct in terms of carbon emissions and ecological effect. Additionally, small trees are more susceptible to death by fire than large trees. Possibly, the short rotation ages common in industrial forests contribute to the higher incidence of high-severity fire on those lands. However, canopy height as estimated from Landfire was not associated with fire severity in preliminary analyses. Finally, we used extended assessment severity estimates, which compare pre-fire imagery to imagery taken 1-year post-fire. In contrast, initial assessment estimates compare pre-fire imagery to imagery taken 1–3 months post-fire. While extended assessments are more accurate (Lydersen *et al.* 2016), they can be impacted by post-fire management (eg salvage harvesting), potentially leading to overestimation of high-severity effects (Safford *et al.* 2015). To investigate this potential bias, we examined the aforementioned 2007 Moonlight Fire, for which extensive salvage logging occurred on private industrial forestland. We found a slight increase in the probability of a pixel burning at high severity in the extended versus initial assessment: 0.017. However, this proportion was small relative to the observed difference between private industrial and public land throughout our entire dataset (0.017 versus 0.14) and fell within the reported classification error for the dataset (Miller *et al.* 2009; see WebPanel 2).

Fire is a complex natural process that occurs on land managed in diverse manners, for diverse objectives and in a wide array of socioeconomic and political contexts. Here, in investigating fire-severity patterns across major forest ownership classes, we discovered that the incidence of high-severity fire is clearly increased in and near private industrial forests. The heightened likelihood of high-severity fire both on and around industrially managed forests suggests that the predominant forest management practice on these lands (even-aged plantation forestry) may contribute to the broader pattern of increased high-severity fire incidence in California on land of all ownership types. This, together with the complex intermix of ownership types and evidence that high-severity fire effects may be spread across ownership boundaries, emphasizes the necessity of cross-ownership cooperation to reverse recent, concerning trends in extreme fire effects.

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Data Availability Statement

All data used in this study are freely available (accessible either through the publications cited below or within this article's Supporting Information) with the exception of the property boundaries of private industrial timber companies in California, which cannot be publicly posted due to issues of privacy and data ownership. Related queries should be directed to the corresponding author of this study. All code used in the processing and analysis of data in this paper can be found on Github (https://doi.org/10.5281/zenodo.6338495).

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