Forest Ecology and Management 537 (2023) 120959

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Perspective

The Wind River alder strip revisited: Lessons for post-fire management on recent and future western Washington and Oregon fires

Bernard T. Bormann [a,*], Courtney R. Bobsin [a], Robert J. McGaughey [b], John C. Gordon [c], Brett A. Morrissette [d], Ally Kruper [a]

[a] Olympic Natural Resources Center, University of Washington, Forks, WA 98331, USA
[b] Pacific Northwest Research Station, USDA Forest Service, Seattle, WA 98195, USA
[c] Yale School of Environment (emeritus), Yale University, New Haven, CT 06520, USA
[d] College of Forestry, Oregon State University, Corvallis, OR 97331, USA

ARTICLE INFO

Keywords:
Red alder
Fire buffer
Long-term productivity
Site index
Post-fire management
Labor-day fires
C sequestration

ABSTRACT

A forester set up a large-scale, 1600-m fire-break trial with red alder (*Alnus rubra* Bong.) inter-planted between Douglas-fir (*Pseudotsuga menziesii* Mirb Franco), after the extensive 1927 Yacolt Burn in the Columbia Gorge. This now 90-year-old trial demonstrates dramatic effects of alder on soils and growth of Douglas-fir; it also provides a timely lesson for foresters deciding what to do after recent similar fires in western Oregon and Washington. We used 2015 airborne lidar to re-examine the trial effects. Douglas-fir trees in stands mixed with alder (Strip) continue to grow taller than those in adjacent pure stands (Controls), even though almost all alder died out 30–40 years ago. Site index in Strip stand continues to increase relative to Controls, now averaging 30–40 % higher than Controls. Basal area ha^{-1} is 2.1, and stem biomass is 2.8 times higher in Strip than Control stands. Implications and future studies are discussed. Before planting wall-to-wall Douglas-fir, foresters responding to new fires in this region might contemplate alder interplanting and crop rotation for their likely positive effect on future revenue, wildlife, and carbon sequestration rates and storage above and belowground.

1. Introduction

1.1. Policy and historical context

Deeper reflection on how to manage forests after intensive wildfire is needed in regions where its incidence is increasing, as appears to be the case in the coastal Pacific Northwest (west of the Cascade Mountain crest in Oregon and Washington, USA). Evidence for a return to a period of more frequent high-intensity fire in this region comes from the historical record. Although systematic recordkeeping of wildfire in Oregon and Washington began around 1960, researchers have re-constructed regional fire extents back to the 1920s (Fig. 1).

These records establish a period of large fires until about 1940, followed by roughly 60-years with more effective fire suppression combined with a milder climate (Westerling et al., 2007). We refer to these as the “historic-mega-fire” and “fire-exclusion” periods. Fire history before 1920 is less well known, but accounts and records indicate an earlier start date for the mega-fire period. Between about 1850 and 1920, there were 5 fires each over 200,000 ha in western Oregon including the Yaquina, Silverton, Great fire, and Siletz, as well as first Yacolt Burn in southern Washington (Morris, 1934). Fires between 40 and 200 k ha during this time are too many to list here. Two examples from near-coastal areas are a series of fires across the north and east ends of the Olympic Peninsula (Pinchot and Smith, 1909) and the 1868 Coos fire that burned what became the Elliott State Forest on the central Oregon Coast (Morris, 1934). The Government Land Office cadastral survey records, many collected in the late 1880s, describe large areas of western Oregon as “brush with a scattering of fir,” supportive of this fire history (Bormann et al., 2015). Large fires are not well documented before about 1700, although purposeful under-burning and the creation of non-forested prairies via fire by indigenous communities likely reduced them (Boyd, 1999); we do not know by how much. The historic-mega-fire period ended with the 1902–1927, 200 k-ha Yacolt Burn in SW Washington and the 1933–1945, 290 k-ha Tillamook Burns in NW Oregon.

The 2002 Biscuit Complex Fire covering over 300 k ha in coastal SW

* Corresponding author.
E-mail addresses: bormann@uw.edu (B.T. Bormann), cbobsin@uw.edu (C.R. Bobsin), robert.mcgaughey@usda.gov (R.J. McGaughey), jgordon@iforest.com (J.C. Gordon), brett.morrissette@oregonstate.edu (B.A. Morrissette), akrup99@uw.edu (A. Kruper).

https://doi.org/10.1016/j.foreco.2023.120959
Received 15 February 2023; Received in revised form 17 March 2023; Accepted 21 March 2023
Available online 29 March 2023

Oregon seemed to indicate the end of the fire-exclusion period in this region. Any lingering questions were put to rest with the recent large fires in Oregon collectively called the Labor Day fires of 2020. These fires destroyed thousands of homes and burned over 390 k ha—nearly 15 billion board feet of timber, worth an estimated $30 billion on private and public forests and timberlands (Rasmussen et al., 2021) (Fig. 2). Other recent fires in the region add to the level of concern, such as the 2017 Eagle Creek fire, and 2022 fires including the Cedar Creek fire east of Eugene, OR and the Bolt Creek fire northeast of Seattle, WA.

We surmise that forest policies and practices developed during the fire-exclusion period with infrequent and small fires may no longer fit well with current conditions. There is one long-term trial initiated in the historic-mega-fire period—the Wind River alder-strip study, described and analyzed below—that is uniquely suited to informing development of new approaches to forest management. This study was based on societal perspectives during the period in which it was implemented. Repeated fires traumatized Pacific Northwest residents sufficiently to facilitate fervent, but often short-lived debate (Morris, 1934). For example, the news media reported on the impact of loss of life and timber volume in the 1902 Yacolt fire (estimated at 12 BBft in 3 counties). The fires had major effects on long-term timber supply and community economies. The debate led to policy changes in some cases, perhaps most notably after the Yacolt Burn—which is often cited as initiating fire exclusion practices (Cowan, 1961). Most of historic debate tended to be understandably focused on what caused and how to fight future fires. Over the past 30 years, debate has focused on how specific forest practices including harvesting, thinning, and underburning, and climate influence fire behavior, especially on fires in drier forests.

Less frequently debated is the effect of intensive fire on long-term ecosystem sustainability (Bormann et al., 2017). By the time trees grow back, the memory of the fire fades—and the role of fire in lowered productivity becomes less obvious. With major forestry research investments over the last 50 years, we know that many less productive Douglas-fir (*Pseudotsuga menziesii* Mirb Franco) stands in the Pacific Northwest respond well to nitrogen fertilizers (Edmonds and Hsiang, 1987). We also now know of the large cumulative loss of nitrogen and mineral soil organic matter that can result from intensive fire. This is best known from a long-term study where soils were extensively sampled a few years before they were intensively burned in the Biscuit fire in SW Oregon (Bormann et al., 2008). Repeat, post-fire sampling showed losses of 23 % of nitrogen and 31 % of soil organic matter from the soil profile. Follow up studies suggested these changes drove a 50 % decline in net primary production the first 8 years post fire (Bormann et al., 2015). Researchers have wondered if such soil and growth effects will persist to affect the entire lifespan of stands. Slashburning was widely practiced in the mid to late 1900s. It's effects on productivity have yet to be fully assessed but these burns were conducted when fuel moistures were low enough with the intent of reducing fire intensity low enough to avoid severe soil damage.

Whether new policy and research will emerge from recent western Oregon and Washington fires is not yet clear. Their immediate damage, including losses of life and structures, and weeks-long widespread toxic smoke plumes, garnered widespread regional and national attention.

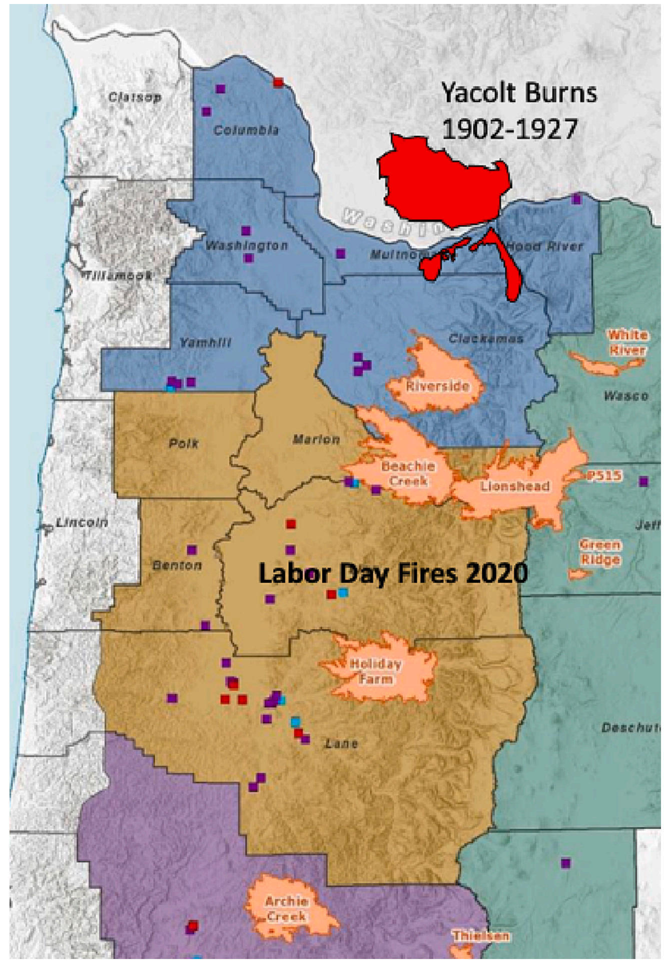

Fig. 2. The 1902–1927 Yacolt Burns and the 2020 Labor Day fires—based on map in Rasmussen et al. (2021).

Current and future timber volume losses on thousands of acres of forest industry lands also raises the question about whether Douglas-fir monoculture is helpful or harmful (Sickinger, 2019).

1.2. The Wind River alder-strip study

Serendipity and foresight from early researchers at Wind River, near Stevenson, WA, give us a new opportunity to address post-fire-exclusion concerns, and to address the question: *How much timber production lost from soil damage could have been avoided if long-term sustainability and soil restoration had been considered during post-fire planning?* By taking a broad perspective, we can also ask about forgone carbon sequestration, options for late-seral habitat, and climate adaptation.

One of the oldest forest research trials in the region was initiated in the Wind River Experimental Forest, near the Columbia George in the

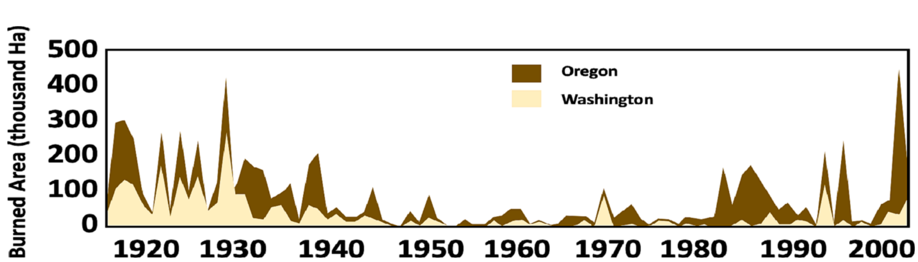

Fig. 1. Wildfire from 1915 to 2005 in Oregon and Washington—modified from Bormann et al. (2006), using data compiled by David L. Peterson, School of Environmental and Forest Science, University of Washington.

southern Washington Cascades following the 1927 Yacolt burn, thought to be a reburn of the original Yacolt Burn of 1902. This trial provides insight into the research questions of the mega-fire period. This trial was designed to compare two post-fire management alternatives: (1) operational planting of Douglas-fir over several thousand acres across the burned area, and (2) a 1.6-k-long, 22-m-wide linear strip following a surveyed section-line boundary where red alder (*Alnus rubra* Bong.) was interplanted between Douglas-fir as a fire break buffer with the goal of limiting spread in future fires. As one of the earliest widespread planting trials after fire or harvest, seed from Puget Sound stands of Douglas-fir and alder were grown in the new Wind River Nursery before being planted out. Harrington and Reukema (1983) describe planting of 1-1 Douglas-fir seedlings in 1929. Mixed stand development was affected by poor early growth of alders that suffered from Fall and then Spring frosts and browsing after planting in 1933 (Miller and Murray, 1978). Likely effects of non-local seed sources and massive soil C and N losses from repeated intense fire cannot be disentangled looking back (DeBell et al., 2002) and will have to be addressed in future studies.

This trial never was exposed to a subsequent fire but provided crucial evidence about the effects of alder on post-fire soil properties and growth in mixed stands compared to the dominant regional practice of Douglas-fir monoculture. Evidence from this alder-fir mixture trial and other studies did not lead to extensive application in the Pacific Northwest—perhaps in part because wildfire in western Oregon and Washington was diminished during the fire-exclusion period.

The Wind River alder strip was designed by Leo Isaac, a pioneering silviculturist with the Forest Service, to test whether interplanting alder between planted Douglas-fir would act as a fire break. A later account (Tarrant, 1978) described a conversation with Isaac, where a member of the planting crew made a bet that if alder had been there, the fire would have been stopped—based on observations that wildfires tended to stop when they encountered alder stands. Apparently, Isaac planted the strip from a riparian zone—where alders are more common—up and over hilly uplands to dampen fire spread. With the recent return of intensive fire to western Oregon and Washington, others have been observing this alder/hardwood effect. Unfortunately, Isaac's trial was never tested by a wildfire, so whether it would affect fire progression remains uncertain.

We would probably not know of this trial if it were not discovered by Robert F. Tarrant, a pioneering scientist in the Pacific Northwest who, when studying soils in the Wind River Experimental Forest in 1948, came upon a young stand of trees regenerating after the Yacolt Burn, with a mixture of red alder and Douglas-fir (described in Tarrant, 1978). He noted how much cooler the air temperature was, that needles were greener, and the litter thicker. Tarrant initiated research into alder in the Pacific Northwest a decade or so later by examining the conditions in the mixed alder strip compared to adjacent control stands lacking alder (Tarrant, 1961). Twenty-seven years after planting alder, he observed higher soil nitrogen and organic matter, but average Douglas-fir diameters and heights did not significantly differ with or without alder intermixture. He did note small increased growth of stems and crowns in dominant Douglas-fir trees in the mixed alder-fir "Strip" stands which foretold future responses. Tarrant and Miller (1963) indicated that the forest floor in the alder Strip had 17 % more dry mass, and that mineral-soil organic matter concentrations had increased 32–40 % in the upper 30 cm relative to pure Douglas-fir "Control" stands. They also observed a 14 % decline in bulk density associated with soil aggregation and increased organic matter. The large increase in mineral soil nitrogen from 520 to 692 kg N ha^{-1} to a depth of 91 cm, a 33 % increase, was attributed to N_2 fixation. Federal researchers returned to evaluate tree growth on the study at age 48 (Miller and Murray, 1978) and found a distinct increase in average height growth of Douglas-fir trees growing with alder; these trees were 14–34 % taller than trees not mixed with alder in adjacent Controls. Additionally, when measuring the tallest 20 % of trees, they noted an increase in site index of 13–33 %. Stand wood volumes were more dramatic, increasing 95 % when also counting the alder volume (Douglas-fir volumes were only 7 % higher). They also established that effects of interplanting alder increased moving up the hill away from the riparian zone. For example, increases in height (Strip versus Controls) increased from 14 to 34 % from the bottom to top of the hill. A group of university researchers evaluated the study in 1984 at age 55 years (Binkley et al., 1992). They estimated increases in biomass of 70 %, aboveground net primary production of 115 %, soil organic matter mass of 41 % and total N to 90 cm of 40 % relative to Controls. Miller et al. (1993) returned to spatially evaluate growth effects along the Strip moving to Controls on each side. They established that the Strip stands outpaced adjacent Control stands to the west more than the east. DBH increases were higher on the west (63 %) compared to the east (14 %). Similarly, tree height increases were larger relative to the west (50 %) compared to the east (22 %). Stem volume increases were also larger to the west (248 %) compared to the east (53 %). The east Controls tended to be downhill and downwind from the Strip. An individual-tree N fertilizer trial was overlaid on northern part of the trial in 1984 (Miller et al., 1996), where 180 individual dominant Douglas-fir trees 15-m apart were randomly treated in a 3.6-m radius with either 2 kg Urea, 2.7 kg Ammonium Nitrate, or 2.5 kg of Biuret N fertilizers; 60 trees were Controls. Although little response was observed in Strip trees, East Controls trees saw a 22–28 % increase in 8-yr total stem volume growth (m^3), while West Controls had an 11–14 % response. The effect of this study on interpretation of the alder strip seems minimal as the total application, to the north end of the study amounted to a dispersed application of only about 30 kg N/ha equally across the Strip and Control. Given the N-limited status, added fertilizer could only be expected to dilute the alder effect. The stands were last revisited by Binkley (2003). This accounting observed a flattening of growth, with Douglas-fir stem mass stagnating at 120 Mg ha^{-1} in the Controls stands, while growth continued in Douglas-fir in the strip, after nearly all alders had died, increasing to 230 Mg ha^{-1}. We revisit these findings in the Discussion to look at emerging spatial and temporal patterns. This paper reports on a new re-measurement—using airborne lidar technology—of the Wind River study to better observe long-term changes and what drives them, and to apply this to better inform future post-fire management in western Oregon and Washington.

2. Materials and methods

The Wind River alder strip lies at about 600 m (2000 ft) elevation in the western edge of the Wind River Experimental Forest north of Stevenson, WA, at approximately 45.811°N 122.006°W. The soils are moderately deep, well-drained and of volcanic origin. Precipitation is 244 cm (96 in) falling mostly November to March. This fire affected area is described as typical of lower productivity stands in western Washington (Miller and Murray, 1978).

Lacking resources for an extensive ground-based remeasurement, we started by examining historical aerial photography available on Google Earth. This revealed a clear strip of taller trees, even shading some shorter adjacent stands. We then obtained airborne lidar point clouds flown in 2015. Laser scanning data were acquired for the study area between July 15, 2014 and August 5, 2015 using a Leica ALS 70 sensor with regionally standard sensor and flight parameters (Table 1).

The study area was surveyed with opposing flight lines and side-lap

Table 1
Flight parameters and sensor settings.

Survey altitude (AGL)	1400 m
Pulse rate	198 kHz
Pulse mode	Single pulse in air (SPiA)
Field of view (FOV)	30°
Roll compensated	Yes
Overlap	>100 % with 60 % sidelap between flightlines
Pulse emission density	≥8 pulses m^{-2}
Aggregate pulse density	14.83 pulses m^{-2}
Ground point density	1.50 points m^{-2}

greater than 60 % ensuring at least 100 % overlap for all parts of the study area. Vertical accuracy of the data was evaluated using 2,269 ground survey points collected in open areas using Real Time Kinematic (RTK) and Post Processed Kinematic (PPK) survey techniques. Vertical RMSE for the data was 3.5 cm with a standard deviation of 4.2 cm. Lidar data are available from the Washington Lidar Portal (https://lidarportal.dnr.wa.gov) for the project labeled "WASCO B 2015".

For our analysis, we started by identifying the point-cloud tiles from the 2015 lidar project covering the alder Strip and surrounding Control areas (Fig. 3). Working in R Studio (version 2022.02.0) with the lidR package (version 4.0.0) (Roussel et al., 2020), the target area around the alder strip was clipped from the point cloud. Then, the point cloud was normalized relative to the ground surface. A canopy surface model was created using the normalized point cloud to produce a canopy height model (CHM).

Using ArcGIS Pro, we manually created 18 Strip, 36 Buffer, and 36 Control polygons enclosing stands of trees with similar densities and heights, based on visualization using Fusion software (Fig. 4) (McGaughey, 2009).

The original study was not a randomized experiment, rather it was designed as an operational trial to test whether the mixture would function as a fire break to stop lateral fire advance. As such, it was laid out directly up a fairly uniform slope along a township/range section line. This provides a topographic comparison minimally biased from a soil or site perspective. We defined the Strip treatment as the stands centered on the original alder planting described as 22 m wide (Tarrant, 1961), extending 6–21 m to the sides to include current Douglas-fir of visually similar height and stand density, and thus likely alder influenced. This approach builds on the analyses of Miller et al. (1993) showing extended alder effects, but it may have diluted the alder-mixing effect. We defined the Control treatment as the stands extending about 25-m on both sides, past a 10-m buffer to avoid mixed effects. These stands were also delineated to have visually uniform tree height and density.

We also evaluated a longer length of the Strip and Controls than in earlier studies, described as 1600-m long in Tarrant (1961). The northern 400 m of the Strip has been the focus of previous research. We extended our analysis another 300 m to the south through an area with some major topographic dissimilarities including nearby steep hills and small water courses crossing the area. We did this to examine how much influence topographic factors might have, and to better understand if wider inference from the study was possible. We did not examine the southernmost portion of the Strip, where it crosses a major stream and riparian area with abundant natural alder regeneration (see Fig. 3), mainly because we were uncertain of the original installation. We also identified portions of the Strip and Controls used in previous studies

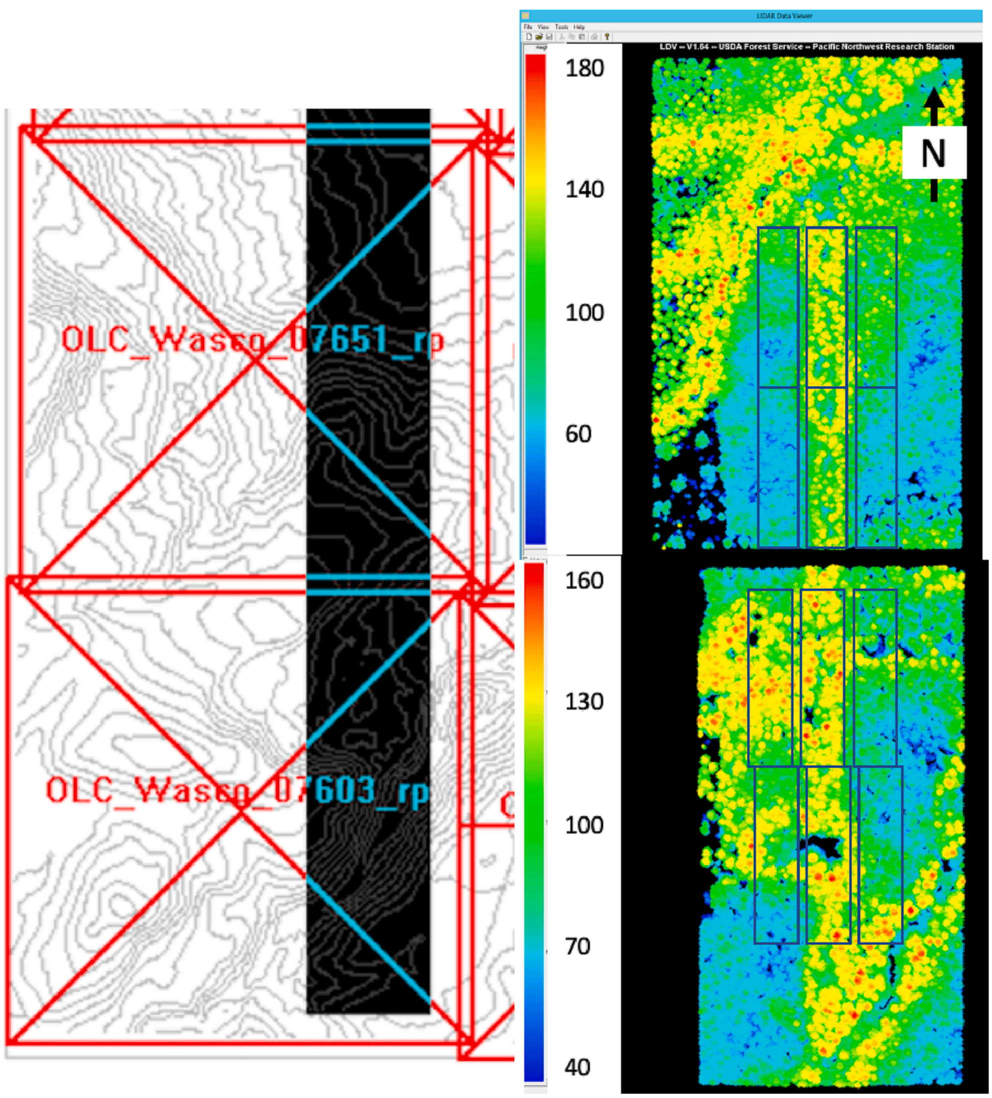

Fig. 3. Fusion visualization of two 2015 lidar tiles showing evidence of height differences in the Wind River alder Strip (central column) relative to adjacent Control areas. The color ramp for the canopy model is in feet.

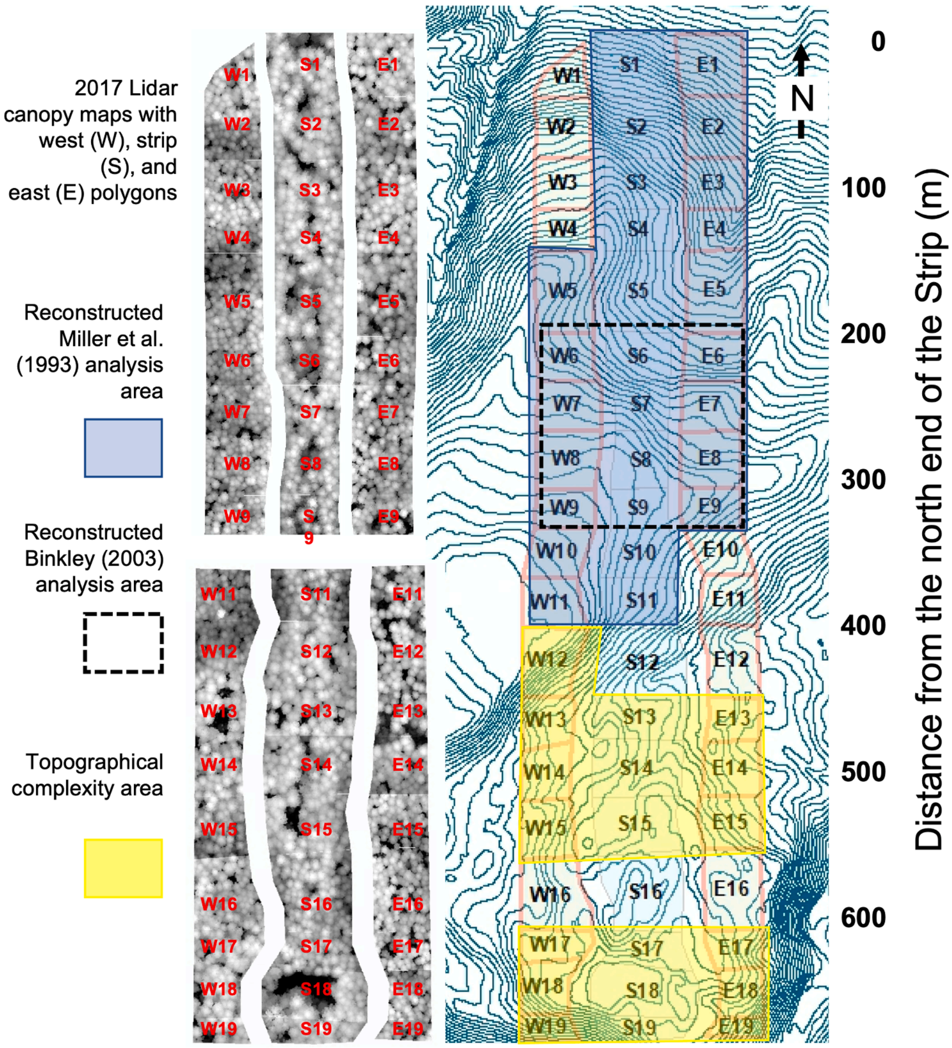

Fig. 4. Left side with a 2017 lidar canopy model divided into sub-sample boxes on numbered west (W) and east (E) controls and alder-strip (S) polygons in the middle. Right side with lidar-derived contours and area analyzed by Miller et al. (1993) and polygons designated as having topological incongruities.

(Fig. 4). These areas were reconstructed based on a map of the area sampled (Miller et al., 1993) and sampling descriptions in Binkley et al. (1992) and Binkley (2003).

Polygons were used to clip the CHM and the clips were exported as raster files into R Studio to identify individual trees. The occasional trees under 8 m were not included to exclude any possible younger age class (Fig. 5).

Using the FindTreesCHM function in the rLiDAR package, individual trees were identified and tree heights calculated for further analysis. We recognize that our lidar-based approach likely underestimates stand density. Our approach uses an algorithm that identifies a single maxima within a 0.75- by 0.75-m area of the CHM. If there are actually two (or more) trees within this area, only one will be detected and counted in the estimate of trees per unit area. Suppressed trees can be “hidden” when their tops are enmeshed in the side canopy of a larger tree. Few suppressed trees or snags were observed during a 2021 walkthrough, but a bias could be present if Control and Strip stands had different proportions of very close or hidden-suppressed trees. Future studies may want to evaluate this possible effect.

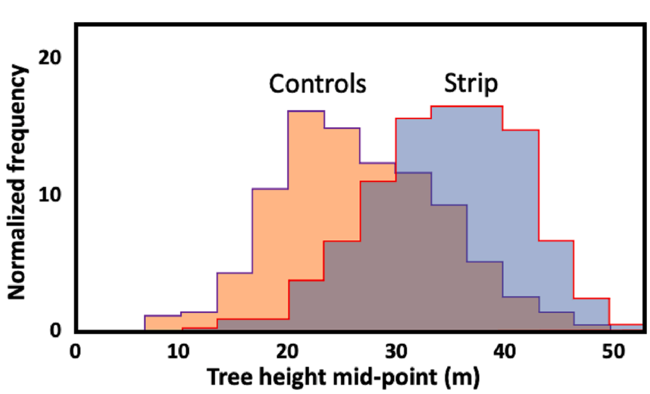

Fig. 5. Frequency distributions of lidar-detected tree heights.

Our confidence in the measurement of tree height using a lidar based methodology is based on a regional study (Andersen et al., 2006). Lidar at this return density has a tendency to produce a first return at the top whorl of branches, hence underestimating total height by the length of the leader. Regionally this was determined to be 0.7 ± 0.4 m for Douglas-fir trees. Lidar heights also are affected by slope when trees lean—underestimating height when they lean uphill and overestimating when they lean downhill. Gatziolis et al. (2010), using an earlier generation lidar sensor, found that greater underestimates of height are possible if dense understory is misconstrued as ground, especially in riparian areas. The Wind River stands are lower productivity than the stands they studied, lack an overly dense overstory or understory, and have relatively modest slopes. Andersen et al. (2006) also note that careful ground measurements of height have uncertainty and also underestimate height by 0.3 ± 0.3 m. We conclude that any lidar-derived underestimates of height are most likely 50 cm or less (about 1 % of total height) and will be present with similar magnitude in Strip and Control stands. We made no adjustments in estimates to err on the side of being conservative in this comparative analysis.

To estimate diameter at breast height (DBH) for individual trees, we used a regional height equation for Douglas-fir (Hanus et al., 1999):

$$Height = 4.5 + e^{\left(7.2622 - 5.9 * DBH^{-0.2872}\right)} \tag{1}$$

and solved for DBH:

$$DBH = \left(\frac{ln\left(\frac{Height - 4.5}{e^{7.2622}}\right)}{-5.9} \right)^{\frac{1}{-0.2872}} \tag{2}$$

where: *Height* is total tree height in feet calculated from the lidar CHM and *DBH* is diameter at breast height (1.37 m or 4.5 feet) in inches.

We recognize that these diameters are approximations since taper may vary between Strip and Control trees and alter estimates somewhat. To cross-check, we examined how well this approach worked on 57-year-old Douglas-fir trees measured by Miller et al. (1993) on this site, as well as 141 Douglas-fir trees on the Willamette long-term ecosystem productivity study near Vida, OR in the Oregon Cascades with similar age, DBH, heights, soil, and fire history. Biomass estimates were then calculated using estimated DBH from equation (2) and the methodology of Binkley (2003) with regional biomass equations for Douglas-fir (Means et al., 1994). Biomass estimates were only produced for the area sampled by Binkley (Fig. 4) to facilitate comparison.

3. Results

Airborne lidar flown in 2015 over the entire Wind River alder Strip and the larger area surrounding it provides a broad view of potential alder-strip effects. Average height of all lidar-identified trees in subsampled Strip stands are considerably taller than those in Control stands on either side, averaging 21 %–34 % taller depending on which samples are included (Fig. 6).

The choice of which subsamples to include in the average (see Fig. 4) did not seem to affect relative height difference (Strip to Controls). For example, when areas with complex terrain (steep slopes and small streams) are removed from the average, the same effect is observed, although east and west Controls shift.

Site index—based on height and age of the tallest 20 % of trees identified by lidar, using King (1966) with a 50-year index age—shows even more differentiation with Strip trees at 139 ft and Controls at 97 ft (West) and 107 ft at 50 years (East). This corresponds to an increase from a mid-site IV to an upper-site III. Differences indicate a relative increase of 43 % (to west) and 30 % (to east). Site index was quite closely related to slope position in Control sample areas (Fig. 3). Height of site trees declines as expected moving up the slope away from the riparian areas that are assumed to have more moisture, soil organic matter, and soil depth. In the Control polygons, height of the tallest 20 % of trees drops sharply, more so on the West than East Controls. Douglas-fir trees with alders intermixed show far slower decline with distance from the riparian area (Fig. 7).

The slopes of the fitted lines relating tree height and distance from the riparian area are −0.13 (West) and −0.05 (East) compared to −0.02 m m^{-1} in the Strip; or 83 % (West) and 42 % (East) greater than in Controls. Since alders are thought to grow more slowly in drier conditions relative to Douglas-fir, this result seems non-intuitive at first.

Differences in stand density of trees were surprisingly small and insignificant, given the considerably larger size of the Douglas-fir trees in the alder-strip. Stand density identified by lidar (highest hits greater than 8 m) was 534 trees ha^{-1} (±110 95 %CI) or 216 trees ac^{-1} in Strip stands and 523 trees ha^{-1} (±10 95 %CI) or 211 trees ac^{-1} in West Controls, and 500 trees ha^{-1} (±13 95 %CI) or 202 trees ac^{-1} in East Controls. The higher variability in Strip stands may reflect different stand development patterns linked to previous alder presence.

Differences in tree diameters—estimated for individual trees using lidar-derived heights and equation (2)—are large. Average tree-diameters of Strip trees are 29 % larger than in west Controls; 47 % larger relative to east Controls (Table 2). Corresponding basal areas, based on estimated diameters, in Strip stands are 450 m^2 ha^{-1} compared to 255 (west) and 177 m^2 ha^{-1} (east) stands, or 1.8–2.5 times larger.

Cross-checking the lidar equation for estimating diameter from heights was possible by examining diameters and heights for Strip and Control trees as reported by Miller et al. (1993). Diameters so predicted were slightly smaller in Strip (−4 %) and Control (−2 %) than actual diameters. We also compared predicted to actual diameters on a large set of Douglas-fir trees part of the Willamette National Forest's long-term ecosystem productivity study in multiple stands of similar age, size,

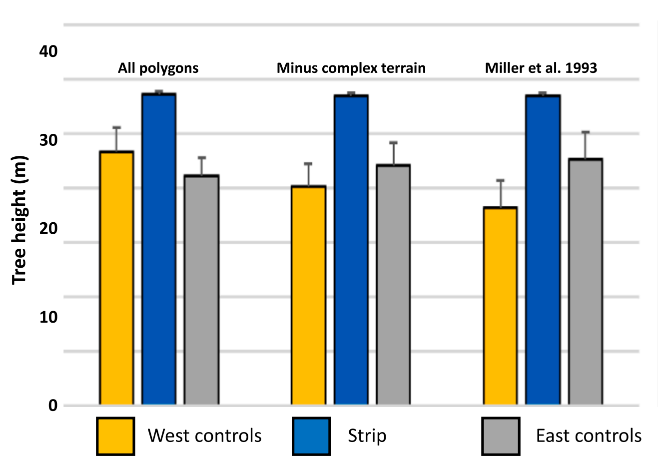

Fig. 6. Average tree height when all subsample boxes are included (left), with complex terrain samples excluded (middle) and when limited to a reconstructed sample by Miller et al. (1993; right)—with 95 % confidence intervals.

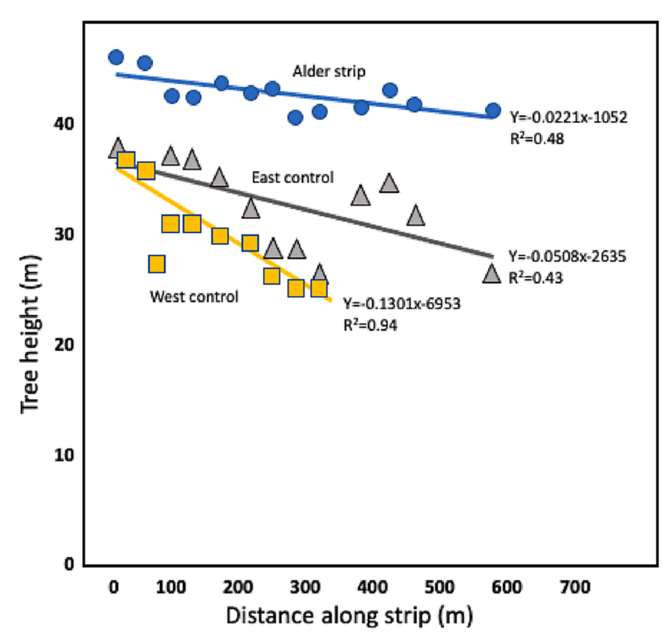

Fig. 7. Height of site trees (tallest 20 %) inside and adjacent to the alder strip showing relationships to slope position (base of hill at 0 m; top of hill at about 350 m; and complex terrain 400–700 m from the riparian zone). Some complex terrain heights are not included in this analysis.

Table 2
Stand metric averages (with ½ 95 % confidence intervals) with basal area and stem biomass derived from tree diameters estimated using lidar tree heights and equation (2).

Metric	Averages				Ratios, Strip to:		
	West Control	Strip	East Control	Both Controls	West	East	Both
Height (m)*	29 (3)	35 (1)	26 (2)	28 (2)	1.3	1.3	1.3
Diameter DBH (cm)*	36 (5)	46 (2)	32 (3)	34 (3)	1.5	1.4	1.4
Basal area (m^2 ha^{-1})*	57 (13)	100 (28)	40 (6)	48 (8)	2.5	2.6	2.6
Stem biomass (Mg ha^{-1})†	111 (73)	333 (144)	130 (32)	120 (42)	3.0	2.6	2.8

† Regional equations are applied to polygons most likely sampled by Binkley (2003) (Fig. 3).
* Height, DBH, and basal area are based on all Strip or Control stands regardless of complex terrain.

elevation, and fire history. In these trees, the equation predicted diameters that were < 1 % higher than actual diameters. Taken together, we conclude that this method had a small effect or bias on predicted DBH. The Strip stands have up to double the number of Douglas-fir trees larger than about 1000 kg tree^{-1} (Fig. 8).

Stem biomass per unit area has become 2.6–3.0 times greater in Strip stands, at 333 Mg ha^{-1} relative to 120 Mg ha^{-1} in Control stands on average (Table 2). Because stem biomass and total stem volume are closely related, larger trees will have substantially more merchantable volume, suggesting substantially greater value. Because carbon is proportional to dry biomass, similar effects are apparent for aboveground C storage. Estimates based on derived diameters have uncertainties because airborne lidar at this return density (8–12 m^{-2}) does not detect some of smaller trees intertwined with or overtopped by larger trees, and snags and live trees are not distinguished. Overall, we expect these estimates to be conservative, especially considering that diameter differences increase when excluding complex terrain.

4. Discussion

Our findings continue the long-term evaluation of this important historical forestry trial in a way that can be more easily applied to the Labor Day and other past and future western Oregon and Washington fires. The original purpose of the Wind River trial was to evaluate alder interplanting as a fire break and this remains untested. Recent western Oregon and Washington fires continue to provide anecdotal evidence

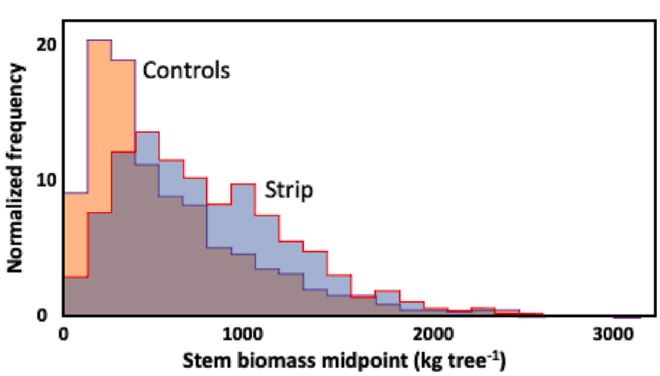

Fig. 8. Normalized frequency distribution of stem biomass in Control and Strip trees.

that alder and other hardwoods dampen fire behavior, presumably because they hold more moisture in foliage, twigs, and bark—which logically consumes fire energy evaporating this water, and therefore acts to dampen or at least slow fire movement, whereas the waxy cuticles on needles and pitch blisters of young Douglas-fir contribute to flammability. For example, the Holiday Farm Fire, one of the Oregon Labor Day fires, entered the Willamette National Forest's Long-Term Ecosystem Productivity experiment with its array of 21 7-ha experimental treatments. Both of the 2 pure Douglas-fir stands in the study the fire entered were burned at very high intensity and severity, while the fire appeared to die out after entering each of the 4 mixed alder, Douglas-fir treatments after killing most alder and fir. How fire would travel through older, alder-influenced Douglas-fir stands, now lacking alder, should also be considered. Douglas-fir trees in the Strip are clearly taller, have thicker bark, and far less understory—so it seems plausible that the Strip might alter behavior or effects of future wildfires.

What the Wind-River alder-strip study best provides are long-term soils, growth and yield, and C-sequestration data on the 85-year effects of growing Douglas-fir and alder together on intensely burned forestland in the Pacific Northwest. Alder interplanting increased mineral soil organic matter to a 30 cm depth by 32–40 % by year 30 and soil N by 33 % to a depth of 90 cm (Tarrant and Miller, 1963). Binkley (2003) followed up and reported a 41 % increase in soil organic matter and a 40 % increase in soil N at year 55, suggesting active N_2 fixation even in the waning years of alder growth. Soil effects and growth of Douglas-fir are linked. Binkley (2003) estimated stem biomass based on diameters as measured by various researchers throughout the life of the stands. He applied regional Douglas-fir biomass equations to estimate stem biomass and found that biomass plateaued in Control Douglas-fir beginning at about 50 years. We were able to approximate the smaller sample area he used (Fig. 3) and apply the same equations to extend the record another 15 years (Fig. 9).

Our estimates suggest that stem biomass has continued to plateau in Controls, while the Strip stem biomass has continued to increase long after alder largely disappeared from the stand, presumably because of soil improvement. This result is consistent with the increasing difference in height, site index, and stand density. Carbon in stem biomass after 55 years in Strip stands is about double that in pure Douglas-fir; increasing to 3-fold after 85 years. Thus, we conclude that interplanting alder on intensely burned soils can lead to major C sequestration benefits, especially when non-stem biomass and soil C increases and possible fire break effects are also considered.

These results are especially important for researchers and landowners now that the fire-exclusion period has ended and intensely burned forests in the region are increasing. We discuss their implications before examining research needs to reduce uncertainties in extending results more broadly to the region. The quite rapid and continuing changes in productivity documented here provide a clear lesson that site index—a principal measure of soil productivity—is not predetermined and unchanging—as is seemingly often assumed by many growth and yield and carbon modelers and C-credit systems. Because site index is the single most important driver in most growth and yield models, site-index changes of this magnitude are likely to strongly influence estimates of future profitability of short-rotation Douglas-fir monoculture, which is widespread in the coastal Pacific Northwest. The real estate investment trusts and timber investment management organizations might want to consider this, especially since the cost of interplanting alder is very small compared to the impact on growth and yield or the cost and carbon footprint of short-lived nitrogen fertilizer effects (Miller and Tarrant, 1983). More studies of where and how broadly red alder timber can be grown for profit, in mixture and pure stands, are needed to fully evaluate combined profitability (see Atkinson et al., 1979).

Little research at the Wind River alder strip has focused on potential wildlife effects. Speeding the growth of trees in plantations to more rapidly achieve late-seral status has been a primary focus on Forest Service lands under the Northwest Forest Plan. The plateau or decline in

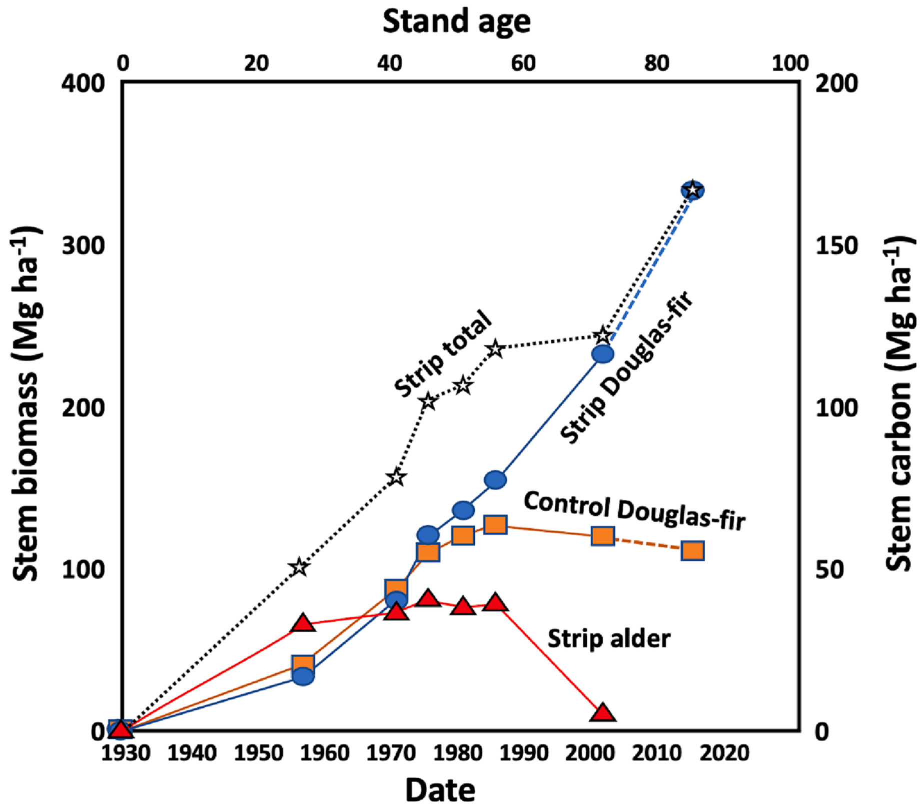

Fig. 9. Stem biomass and carbon, extending Binkley (2003) with our 2015 lidar-based measures (dashed lines).

stand biomass in Controls (Fig. 9) is concerning for late-seral management objectives. Northwest Forest Plan guidance for late-successional reserves largely prohibits harvest after year 80 (USDA and USDI, 1994). Alder interplanting here improved the health of individual Douglas-fir, increasing heights by 30 % over 85 years relative to trees in pure Douglas-fir plantations. Given this, thinning and underplanting with alder or starting over with a mixed stand could be a faster way to achieve late-succession habitat. Binkley et al. (1992) noted an 8-fold difference in understory biomass (higher in Controls), likely resulting from lower leaf areas. Salal (*Gaultheria shallon* Pursh) has been abundant in Wind River Control stands, but they also contain various huckleberries (*Vaccinium* spp.), and beargrass (*Xerophyllum tenax* (Pursh) Nutt.). Forage and non-timber economic values of understory species can benefit from reduced growth of trees and might be beneficial to some landowners. That said, interplanting in strips or other configurations could be designed to provide thermal or other cover, a greater plant and microbial biodiversity, and wildlife-habitat conditions perhaps of benefit more broadly to species other than Douglas-fir.

For land managers not focused alone on short-term-profit or late-seral objectives, the case for interplanting N_2-fixers with conifers after intense wildfire, or rotating pure crops of alders and conifers, is best made when considering climate adaptation and C sequestration. By increasing wildfire frequency and intensity in the Pacific Northwest (Westerling et al., 2007), climate change is causing large direct C and N losses (31 % soil organic matter and 23 % soil N losses in a 2002 SW Oregon fire; Bormann et al., 2008), and later substantially more C losses as fire-killed trees decompose. The Wind River study suggests emergent secondary effects on C sequestration as the new forests grow more slowly, possibly because of losses in soil water- and nutrient-holding capacity and N availability. Strong fertilizer response in trials on stands adjacent to the Strip controls at Wind River (Miller and Tarrant, 1983) confirms N deficiency. Tertiary effects appear likely because increases in N are needed to take advantage of increasing concentrations of atmospheric CO_2 (Mason et al., 2022).

A new series of multi-scaled inquiries and trials are needed to gain confidence in extending results to other intensively-burned forest in this region. The temporal and spatial dynamics of soil productivity effects might be non-intuitive to some. Observed increases in site index are remarkably persistent long after alder is gone and are even expanding over time; in this case over nearly 85 years. Alder influence extends across, up, and down slope from where alders were initially planted (Miller et al., 1993). Our analysis suggests this effect continues to expand reaching up to 22 m in some areas. We agree with Miller et al. (1993) that important effects could have been achieved with fewer alders. We also explored changes with distance uphill from riparian conditions (Fig. 5) which was consistent with data from Miller et al. (1993) but were more pronounced at this later date. The lack of a sharp decline in height and site index moving upslope from the riparian zone in the intermixed stand relative to the Controls is fascinating. At this central Cascade location and elevation, alder is typically thought of as a riparian species—but our results contradict that notion and indicate a possible novel and important role for alder. Increases in soil organic matter and N seem to greatly improve site productivity on these upland soils, at least after intense fire, and this may have particularly valuable application in other intensely burned and nitrogen- or soil-organic-matter-limited conditions.

Extrapolating alder interplanting effects to larger scales such as the entire 200,000-ha Yacolt Burn area would result in large differentials in: (1) value of standing timber; (2) carbon sequestration; (3) early and late-seral habitat potential; and (4) climate adaptation. Further work could examine the entire Yacolt Burn to look for similar conditions in soils and site index, ultimately to gain insights on the state-wide and regional effects of not building back nitrogen and mineral soil organic matter after intense fire. The moderately deep volcanic soils and fire history in the Wind River area are common throughout the western Cascades.

The Labor Day and other recent and future western Oregon and Washington fires would appear to be good candidates for applying these Wind River results, at least experimentally. Many alder-based fire breaks would be needed across multiple landscapes to test the original idea. We would expect to see the largest productivity response in areas with high burn intensity at elevations where red alder can be established. Note that Sitka alder (*Alnus viridis* (Chaix) DC. ssp. *sinuata* (Regel) Á. Löve & D. Löve) grows at higher elevations and has documented positive effects on growth and soils (Harrington and Deal, 1982; Binkley et al., 1984), and other N_2-fixers—such as *Ceanothus* species and legumes—might be candidates as well.

The lidar-based analysis used in this study may have valuable application in extending temporal assessment of other long-term experiments. Many long-term forestry studies in the Pacific Northwest have been largely abandoned given declining budgets and greater emphasis on modeling. The nearby Wind River fertilizer, genetics, and growth and yield trials stand as examples of this, but there are many others, including some in the perimeter of the Labor Day fires, such as the Willamette National Forest's long-term ecosystem productivity study in the Isolation Block area. Major advances in lidar technology, especially drone-based systems with return densities greater than an order-of-magnitude higher, seem to offer great promise in reducing field measurement expenses (Rodríguez-Puerta et al., 2022; Dalla Corte et al., 2020).

Given what we now know about the major C and soil losses with intensive fire in this region (Bormann et al., 2008), this study demonstrates how post-intensive-fire management with Douglas-fir monocultures runs the risk of failing to restore soils, site productivity, profitability, and late-seral wildlife habitat. Resulting declines in productive capacity and long-term soil productivity may even affect the social, economic, and environmental foundations of the region. Including alder planting (e.g., mixtures and crop rotations) may be a viable strategy to recover or possibly even extend many of these attributes, while additionally having a yet-to-be proven benefit of reducing future fire intensity and extent. The déjà vu provided by the recent increase in western Oregon and Washington fires provides an incentive to learn from the past at a critical juncture where historical knowledge is available, and its application and value can be clearly seen. Widespread study could help to begin to reduce this risk on post-fire lands. Perhaps the 2- to 3-fold C-sequestration differential (additionality) shown in this study might also be a source of C credits to fund these studies.

What would Leo Isaac or Bob Tarrant say if they were still with us as we look at how to adapt to recent Western Oregon and Washington fires? We'd like to think they would tell us to try new approaches and follow and test innovative ideas, even if they come from a member of a planting crew. Too much is at stake to keep doing the same thing over and over without deeper reflection.

CRediT authorship contribution statement

Bernard T. Bormann: Conceptualization, Methodology, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Courtney R. Bobsin:** Methodology, Software, Validation, Investigation, Writing – review & editing. **Robert J. McGaughey:** Validation, Resources, Writing – review & editing. **John C. Gordon:** Conceptualization, Validation, Writing – review & editing. **Brett A. Morrissette:** Conceptualization, Validation, Writing – review & editing. **Ally Kruper:** Methodology, Software, Investigation, Writing – review & editing.

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.

Data availability

Data are available from the corresponding author in an Excel spreadsheet.

Acknowledgements

This research was funded by the Olympic Natural Resources Center, (administered by the School of Environment and Forest Science, College of Environment, University of Washington) and the USDA Forest Service, Pacific Northwest Research Station. The work was in part inspired by members of the Alder working group, a stakeholder team organized by the Emerald Edge program of The Nature Conservancy.

References

Andersen, H.E., Reutebuch, S.E., McGaughey, R.J., 2006. A rigorous assessment of tree height measurements obtained using airborne lidar and conventional field methods. Can. J. Rem. Sens. 32, 355–366.

Atkinson, W.A., Bormann, B.T., DeBell, D.S., 1979. Crop rotation of Douglas-fir and red alder: A preliminary biological and economic assessment. Bot. Gaz. (Chicago) 140, S102–S107.

Binkley, D., 2003. Seven decades of stand development in mixed and pure stands of conifers and nitrogen-fixing red alder. Can. J. For. Res. 33, 2274–2279.

Binkley, D., Lousier, J.D., Cromack Jr., K., 1984. Ecosystem effects of Sitka alder on a Douglas-fir plantation. For. Sci. 30, 26–35.

Binkley, D., Sollins, P., Bell, R., Sachs, D., Myrold, D., 1992. Biogeochemistry of adjacent conifer and alder/conifer ecosystems. Ecology 73, 2022–2034.

Bormann, B.T., Darbyshire, R.L., Homann, P.S., Morrissette, B.A., Little, S.N., 2015. Managing early succession for biodiversity and long-term productivity of conifer forests in southwestern Oregon. For. Ecol. Mgmt 340, 114–125.

Bormann, B.T., Homann, P.S., Darbyshire, R.L., Morrissette, B.A., 2008. Intense forest wildfire sharply reduces mineral soil C and N: the first direct evidence. Can. J. For. Res. 38, 2771–2783.

Bormann, B.T., Lee, D.C., Kiester, A.R., Spies, T.A., Haynes, R.W., Reeves, G.H., Raphael, M.G. 2006. Chapter 3, Synthesis: Interpreting the Northwest Forest Plan as more than the sum of its parts. In: Haynes, R.W., Bormann, B.T. Martin, J.R. (Eds.), Northwest Forest Plan—the First Ten Years (1994–2003): Synthesis of Monitoring and Research Results. U.S. For. Serv. Gen. Tech. Rep. PNW-651. Portland, OR.

Bormann, B.T., Perakis, S.S., Darbyshire, R., Hatten, J., 2017. Long-term forest productivity. In: Olson, D.H., Van Horne, B. (Eds.), People, Forests and Change: Lessons from the Pacific Northwest. Island Press, Washington, D.C. pp. 149–160.

Boyd, R.B., 1999. Indians, fire, and the land in the Pacific Northwest. Oregon State University Press, Corvallis, OR.

Cowan, C.S., 1961. The Enemy is Fire!: The History of Forest Protection in the Big Timber Country. Superior Publishing Co., Seattle, WA.

Dalla Corte, A.P., Rex, F.E., Almeida, D.R.A.d., Sanquetta, C.R., Silva, C.A., Moura, M.M., Wilkinson, B., Zambrano, A.M.A., Cunha Neto, E.M.d., Veras, H.F.P., Moraes, A.d., Klauberg, C., Mohan, M., Cardil, A., Broadbent, E.N., 2020. Measuring individual tree diameter and height using GatorEye high-density UAV-Lidar in an integrated crop-livestock-forest system. Remote Sens. 12, 863. doi: 10.3390/rs12050863.

DeBell, D.S., Harrington, C.A., Shumway, J., 2002. Thinning shock and response to fertilizer less than expected in young Douglas-fir stand at Wind River Experimental Forest. PNW-RP-547, Portland, OR.

Edmonds, R.L., Hsiang, T., 1987. Forest floor and soil influence on response of Douglas-fir to urea. Soil Sci. Soc. Am. J. 51, 1332–1337.

Hanus, M.L., Marshall, D.D., Hann, D.W., 1999. Height-diameter equations for six species in the coastal regions of the Pacific Northwest. Forestry Research Laboratory, contribution 25, Corvallis, OR. 11 p.

Gatziolis, D., Fried, J.S., Monleon, V.S., 2010. Challenges to Estimating Tree Height via LiDAR in Closed-Canopy Forests: A Parable from Western Oregon. For. Sci. 56, 139–155.

Harrington, C.A., Deal, R.L., 1982. Sitka alder, a candidate for mixed stands. Can. J. For. Res. 12, 108–111.

Harrington, C.A., Reukema, D.L., 1983. Initial shock and long-term stand development following thinning in a Douglas-fir plantation. For. Sci. 29, 33–46.

King, J.E., 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser For. Pap. 8. Weyerhaeuser Forestry Research Center, Centralia, WA.

Mason, R.E., Craine, J.M., Lany, N.K., Jonard, M., Ollinger, S.V., Groffman, P.M., Fulweiler, R.W., Angerer, J., Read, Q.D., Reich, P.B., Templer, P.H., Elmore, A.J., 2022. Evidence, causes, and consequences of declining nitrogen availability in terrestrial systems. Science 376, 261.

McGaughey, R.J., 2009. FUSION/LDV: Software for LIDAR data analysis an visualization, Version 4.4. U.S. Department of Agriculture, Forest Servic, Pacific Northwest Research Station, Seattle WA, 123(2): 2018. Available online at http://forsys.cfr.washington.edu/fusion/fusion_overview.html; last accessed March 24, 2023.

Means, J.E., Hansen, H.A., Koerper, G.J., Alaback, P.B., Klopsch, M.W. 1994. Software for computing plant biomass — the BIOPAK users guide. U.S. For. Serv. Gen. Tech. Rep. PNW-GTR-340.

Miller, R.E., Murray, M.D., 1978. The effects of red alder on growth of Douglas-fir. In: Briggs, D.G., DeBell, D.S., Atkinson, W.A. (Eds.), Utilization and management of alder. U.S. For. Serv. Gen. Tech. Rep. PNW-70. pp. 386–306.

Miller, R.E., Reukema, D.L., Hazard, J.W., 1996. Ammonium nitrate, urea, and biuret fertilizers increase volume growth of 57-year-old Douglas-Fir Trees Within a Gradient of nitrogen deficiency. Research Paper PNW-RP-490, Pacific Northwest Research Station, Portland, OR.

Miller, R.E., Tarrant, R.F., 1983. Long-term growth response of Douglas-fir to ammonium nitrate fertilizer. For. Sci. 29, 127–137.

Miller, R.E., Reukema, D.L., Max, T.A., 1993. Size of Douglas-fir trees in relation to distance from a mixed red alder – Douglas-fir stand. Can. J. For. Res. 23, 2413–2418.

Morris, W.G., 1934. Forest Fires in western Oregon and Washington. Oregon Hist. Quart. 35, 313–339.

Pinchot III, G., Smith, G.O., 1909. Forest atlas of the national forests of the United States, Olympic folio. The United States Geological Survey, Washington, D.C. Available online at: https://archive.org/details/CAT31299602/page/n1/mode/2up.

Rasmussen, M., Lord, R., Fay, R., Baribault, T., Goodnow, R., 2021. 2020 Labor Day Fires: Economic Impacts to Oregon's Forest Sector. Oregon Forest Resources Institute, Corvallis, OR, p. 104.

Rodríguez-Puerta, F., Gómez-García, E., Martín-García, S., Pérez-Rodríguez, F., Prada, E., 2022. UAV-based LiDAR scanning for individual tree detection and height measurement in young forest permanent trials. Remote Sens. 14, 170. https://doi.org/10.3390/rs14010170.

Roussel, J.R., Auty, D., Coops, N.C., Tompalski, P., Goodbody, t.R., Meador, A.S., Bourdon, J.F., De Boissieu, F., Achim, A., 2020. lidR: An R pachage analysis of asirborne laser scanning (ALS) data. Rem. Sens. Environ. 251, 112061.

Sickinger, T., 2019. Oregon loses $1 billion timber lawsuit to rural counties. The Oregonian. Available online at https://www.oregonlive.com/wildfires/2020/10/oregons-labor-day-wildfires-raise-controversial-questions-about-how-forests-are-managed.html; last accessed May 10, 2022.

Tarrant, R.F., 1961. Stand development and soil fertility in a Douglas-fir-red alder plantation. For. Sci. 7, 238–246.

Tarrant, R.F., Miller, R.E., 1963. Accumulation of organic matter and soil nitrogen beneath a plantation of red alder and Douglas-fir. Soil Sci. Soc. Am. Proc. 27, 231–234.

Tarrant, R.F., 1978. Attitudes toward red alder in the Douglas-fir region. In: Briggs, D.G., DeBell, D.S., Atkinson, W.A. (Eds.), Utilization and Management of Alder. U.S. For. Serv. Gen. Tech. Rep. PNW-70. Portland, OR. pp. 1–7.

USDA and USDI (US Department of Agriculture and US Department of the Interior), 1994. Record of decision for amendments to Forest Service and Bureau of Land Management planning documents within the range of the northern spotted owl [plus Attachment A: Standards and Guides]. US Department of Agriculture and US Department of the Interior.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, D.W., 2007. Warming and early spring increases western U.S. forest wildfire activity. Sci. 313, 940–943.