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Decomposition of wood stakes in the Pacific Northwest after soil compaction and organic matter removal

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ABSTRACT

Forest operations can affect soil productivity by impacting the amount and distribution of surface organic matter (OM) and changing the properties of surface mineral soil. The North American Long-Term Soil Productivity Study (LTSP) was developed to address such long-term changes after pulse disturbances associated with clearcut harvesting, soil compaction, and OM removal across a wide spectrum of forest sites. From 2000 to 2002 we established a study to assess the impact of four soil disturbance treatments on OM decomposition in the mineral soil on seven LTSP study plots from southern British Columbia, Canada to southern Oregon, USA. The soil treatments were combinations of two levels of compaction and organic matter removal: 1) removal of only merchantable logs [OM_0] , 2) removal of all the forest floor and woody material [OM_2], 3) no soil compaction after harvest [C_0], and 4) "severe" soil compaction after harvest [C_2]. Aspen (*Populus tremuloides* Michx.) and pine (*Pinus taeda* L.) wood stakes were inserted into the mineral soil of each treatment plot and in an adjacent unharvested control stand to a depth of either 20 or 30 cm (depending on soil depth). At the end of three years the soil compaction and the OM removal treatments had relatively little effect on pine or aspen stake decomposition at the British Columbia study sites. In the United States, soil compaction increased decomposition on the two study sites with coarse-texture mineral soil with surface OM intact. Three key findings were: (1) a strong positive relationship ($p = 0.0009$) between stake water content and stake mass loss, (2) aspen and pine stake decomposition was greater in the clearcut-LTSP treatments than in the unharvested stands, (3) the rehabilitation of the compacted soil treatment on the British Columbia study sites generally increased wood stake decomposition. However, overall, there were no consistent wood stake decay trends across all sites and LTSP treatments.

1. Introduction

Forest harvesting across North America often has significant impacts on soil properties, which may affect future stand productivity (Curzon et al., 2014), or have little impact on forest biomass production (Zhang et al., 2017). Often, the loss of tree overstory results in greater soil temperatures, reduced transpirational water loss, greater snow accumulation, and faster snow melt in spring (Ballard, 2000; Varhola et al., 2010). Loss of overstory, combined with machine trafficking during harvest and site preparation, can further impact both above- and belowground processes (Batey, 2009). Increased soil bulk densities generally reduce water infiltration rates (Startsev and McNabb, 2000; Wagenbrenner et al., 2016), may increase or decrease available water (Ares et al., 2005; Cullen et al., 1991), increase runoff on some soils (Zemke et al., 2019), and decrease soil N availability (Tan et al., 2007; Cambi et al., 2015; Kersey and Myrold, 2021). However, the degree and extent of harvest-related compaction on soil properties is related to equipment used, the number of vehicle passes, soil moisture content (Han et al.,

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2006), surface soil texture (Bock and VanRees, 2002), and amount of logging slash on the soil surface (Han et al., 2009).

Harvest operations and subsequent mechanical site preparation (*e.g.,* slash piling, scarification), especially after clearcut-harvesting, can also cause extensive loss of surface and mineral soil OM (Johnson and Curtis, 2001), which has an important role in soil physical (water-holding capacity, cation exchange capacity, aggregation; Libhova et al., 2018; Solly et al., 2020), chemical (C and nutrient pool size; Slesak et al., 2011; Littke et al., 2020), and biological (N and P cycling or availability; Jurgensen et al., 1997) properties. The majority of soil OM changes after timber harvesting are associated with displacement or decomposition of surface litter layers (Powers et al., 2005; Nave et al., 2010). Loss of surface OM can increase mineral soil temperature (Eaton et al., 2004), reduce available soil moisture (Tan et al., 2007), and decrease nutrient availability (Bhatti et al., 2000; Tan et al., 2009); thereby altering soil processes.

There have been many studies of timber harvesting impacts on soil properties in forest ecosystems and climate regimes across the U.S. and Canada. However, most of these studies were site-specific, had different experimental design parameters, and used a variety of surface and aerial logging systems. Not surprisingly, it has been difficult for forest land managers to extrapolate the results from such widely different studies to help in their management decisions. This problem is being addressed by the Long-Term Soil Productivity (LTSP) study, which was established by the US Department of Agriculture, Forest Service in collaboration with national and international partners across a wide range of forest types and climatic conditions. Using similar harvesting methods and experimental design protocols, the goal of this large-scale study is to measure changes in soil properties from compaction and OM loss and assess their impact on various soil processes and productivity (Powers et al., 2005). Most of the 100 + LTSP installations sites use the same experimental design and have three levels of soil compaction and OM removal in each study replicate, but there are also 'affiliate' sites that use a subset of the core 9 treatment combinations (Powers et al., 2005).

Both soil compaction and surface OM removal have been shown to affect soil microbial activities and OM decomposition (Xu et al., 2015), which have a direct relationship to C pool size and N availability (Baldrian, 2017). Unfortunately, the original LTSP study plan did not have specific protocols for assessing harvesting impacts on soil biological properties, leaving those studies up to local investigators (*e.g.,* Ponder et al. 2016). Other climatic regime and latitudinal gradient decomposition studies have focused mostly on OM placed on surface litter layers (*e.g.,* Johansson et al., 1995; Trofymow et al., 2002; Powers et al., 2009; Currie et al., 2010), and indicated that off-site (regional) climate information, especially air temperature, can be a good predictor of average OM decomposition rates in undisturbed stands. Within a short distance, OM decomposition is often controlled by local climatic conditions (Bradford et al., 2014), but stand age can also be a controlling factor (Hu et al., 2021). After wildfires in Montana, reduced mass loss of wood stakes in the mineral soil was linked to low stake and soil water contents caused by higher summer temperatures (Page-Dumroese et al., 2019). Recent microcosm work also indicated that wood with 60% water saturation maximized wood decay in mineral soil with soil temperatures from 20 to 40° C (Marais et al. 2020).

Different types or quality of OM substrates are used in forest decomposition studies, which makes it difficult to extrapolate results to other sites with different soils and climate conditions (Talbot and Treseder, 2012). However, when a common "standard" substrate is used across sites, OM quality is held relatively constant, and decomposition becomes a function of abiotic and biotic conditions (Jurgensen et al., 2006). Therefore, we used wood stakes of trembling aspen (*Populous tremuloides* Michx.) and loblolly pine (*Pinus taeda* L.) as standard decomposition indices to assess the effect of LTSP harvest treatments on OM decomposition in surface mineral soil of western North American LTSP study sites that span an 11° latitudinal gradient from southern British Columbia, Canada to southern Oregon, USA (Fig. 1). Wood is a normal forest soil component, and its slow decomposition integrates soil changes over extended time periods (Harmon et al., 1986, Chen et al. 2005). Stakes made of aspen and pine have different chemical properties (*e.g.* lignin type, lignin to cellulose ratio, N content, C to lignin ratio), which will give information on how soil microorganisms respond to the harvest treatments (Blanchette, 1984; Wang et al., 2018).

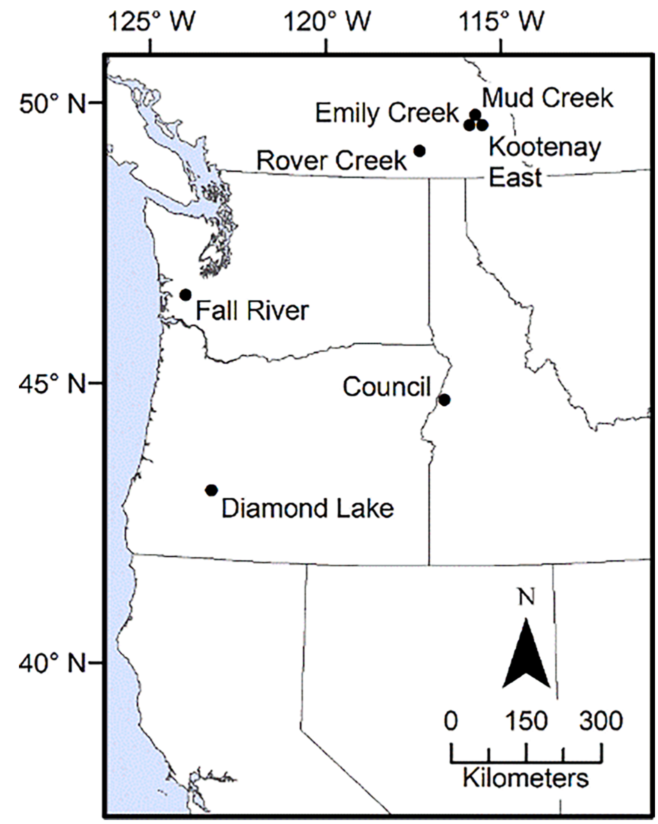

Fig. 1. General location of western North American Long-Term Soil Productivity and affiliate sites used in the wood stakes decomposition study.

Therefore, the objective of our study was to determine the impact of soil compaction and OM removal on wood stake mass loss in the mineral soil along a north – south climate. We hypothesized that: 1) wood stake decomposition would decrease with increasing soil compaction, 2) wood stake decomposition would decrease with increasing surface OM removal, and 3) wood stake decomposition would increase from north to south in response to increasing temperature.

2. Materials and methods

2.1. Experimental design

The LTSP study is a 3 × 3 factorial design combination of compaction: none (C_0), moderate (C_1), and 'severe' (C_2), and surface OM removal: bole only (OM_0), whole tree (OM_1), and whole tree + forest floor (OM_2), as described in Powers et al. (2005). However, due to the number of stakes required and time constraints to install and sample stakes in all nine treatments in each replicate, we only used the 2 extreme levels of compaction (C_0 and C_2) and OM removal (OM_0 and OM_2) treatments in our study (the '4 corner plots' of the 3x3 factorial design). Fall River (Washington) is an affiliate study sites and had only three treatments (C_0OM_0, C_0OM_2, and C_2OM_2), as described in Ares et al. (2005). Soils were compacted with locally available heavy equipment, which were supposed to compress the soil to 80% of root-limiting bulk density in the 'severe' (C_2) treatment (Powers et al., 2005). However, not all sites were able to achieve that compaction level (Page-Dumroese et al., 2006), and at our study sites the C_2 compaction had bulk density increases ranging from 64 to 86%. All sites in British Columbia also had a rehabilitation treatment, in which the compacted soil was broken up with an excavator bucket and the forest floor mixed into the surface mineral soil. If possible, our study plots were placed in LTSP treatments that received herbicide applications (Council, Fall River) or manual brushing (British Columbia sites, Diamond Lake). We also established study plots in adjacent unharvested stands to assess OM decomposition in unharvested, undisturbed mineral soil during the study period. The seven LTSP installations and general site information are shown in Table 1.

2.2. Wood stakes

Trembling aspen and loblolly pine were used as standard substrates on all sites, and stake construction follows the protocol in Jurgensen et al. (2006). The top of each stake was treated with a wood sealer to reduce moisture loss after installation. Two 10 m × 10 m subplots were established in each LTSP treatment, rehabilitation, and unharvested control plot, and 25 stakes of each species were inserted vertically into the mineral soil of all subplots to a depth of 30 cm (20 cm in the shallower Canadian soils), so that the top of each stake was level with the mineral soil surface. If the forest floor was still present (OM_0 plots), it was replaced on top of the stakes. To minimize soil compaction at the wood-soil interface, stakes were placed into holes approximately 30 cm apart made with a square 2.5 cm soil coring tool. Stakes were sampled for three growing seasons and five stakes of both species were randomly selected from each subplot, weighed in the field to obtain wood stake water content (in percent) at the time of extraction, and subsequently sent to the College of Forest Resources and Environmental Science, Michigan Technological University, Houghton, Michigan for immediate processing. In the laboratory, stakes were cleaned of adhering soil, dried at 105° C for 48 h, and weighed. Stakes not sampled during the first three growing season were left in the soil for later sampling.

Wood decomposition (mass loss) at each extraction was determined by comparing dry weight of each field stake with the weight of its corresponding control (t_0) section (wood block not placed in the field). Additional details on wood stake mass loss calculation are presented in Jurgensen et al. (2020). In this paper we present results of wood decomposition at the seven LTSP study sites three growing seasons after stake installation.

2.3. Study sites

2.3.1. British Columbia, Canada

The four British Columbia sites are within two biogeoclimatic zones. Rover-Sedlack is located in the Interior Cedar-Hemlock biogeoclimatic zone ("the wetbelt"); and Emily Creek, Mud Creek, and Kootenay East sites are located in the drier Interior Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) biogeoclimatic zone and influenced by the rain shadow effect of the Coast, Cascade, and Columbia Mountains (Berch et al., 2019). All sites have a slope < 15%, and a volcanic ash component in the surface soil, resulting in a fine sandy-loam texture. The stands were harvested between 1997 and 2002 and one replicate of each LTSP treatment was established. Harvesting was conducted at all sites during the winter to avoid compaction or OM displacement. Trees were hand-felled with line skidding to access corridors. Slash and OM removal treatments were completed in the summer following harvesting by hand or with an excavator working in buffer strips. At Rover-Sedlack compaction was achieved with a rubber-tired skidder with an 1818-kg concrete block attached to the back. The skidder drove back and forth in an overlapping pattern until the desired compaction was achieved. Compaction around stumps was achieved using a hand compactor. At the other three sites, compaction was achieved with an excavator compacting plate attachment (Berch et al. 2019). More detailed site information can be found in Tan et al. (2009) and Berch et al. (2019).

Emily Creek –The preharvest stand had a mixed conifer overstory of Douglas-fir and ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson). Trees were cut with a feller-buncher and removed with a grapple skidder that did not enter the study plots (Berch et al., 2019). The soil is an Orthic Eutric Brunisol (Soil Classification Working Group 1998), which was derived from limestone morainal deposits, but soil carbonates were not found within the top 30 cm of mineral soil. Wood stakes were installed only in the C_0OM_0, C_2OM_0, C_2OM_2, treatments and rehabilitation plots, as high fire danger at the beginning of the study prevented stakes being installed in C_0OM_2 and unharvested control plots. Consequently, only 400 wood stakes were used on this study site: 2 species × 1 replicate × 4 treatments × 2 subplots × 25 stakes.

Kootenay East – This site had a mixed conifer overstory of Douglas-fir and ponderosa pine. The soil is an Orthic Eutric Brunisol (Soil Classification Working Group, 1998), with a limestone parent material and carbonates generally starting at the 20 cm soil depth. Wood stakes were installed in all four 'corner' treatments, the rehabilitation treatment, and in an adjacent uncut control for a total of 600 stakes: 2 species × 1 replicate × 6 treatments (5 treatments and a control) × 2 subplots × 25 stakes.

Mud Creek – This site had Douglas-fir as the dominant overstory species. The soil is an Orthic Eutric Brunisol (Soil Classification Working Group, 1998) with soil carbonates found within the surface 30 cm. Similar to Kootenay East, all the four LTSP treatments, a rehabilitation treatment, and an adjacent uncut control were used, and a total of 600 stakes installed: 2 species × 1 replicate × 6 treatments (5 treatments and a control) × 2 subplots × 25 stakes.

Rover-Sedlack – This site had a mixed conifer overstory of Douglas-fir and ponderosa pine but is considered more productive than the other three British Columbia study sites. In contrast to the other sites, the soil is classified as an Orthic Dystric Brunisol (Soil Classification Working Group, 1998), which is acidic and occurs on an eolian blanket/veneer with some morainal and glaciofluvial materials (Maynard et al., 2014; Berch et al., 2019). Stakes were installed in all four 'corner' treatment plots, a rehabilitation treatment, and unharvested control. However, many stakes in the C_0OM_0 treatment were destroyed by a wildfire that occurred shortly after installation, so only 500 stakes were used in our

Table 1
LTSP sites used in the wood stake decomposition study and select site characteristics. Average annual air temperature and precipitation are from local weather station data during the study period.

Installation name	Province or State	Average air temperature* (°C)	Average precipitation* (mm)	Elevation (m)	Surface soil texture	Amount of Forest floor removed (kg/ha)[§]
Emily Creek	British Columbia	4.3	483	1200	Fine sandy loam	20,400
Kootenay East	British Columbia	4.3	431	1065	Silt loam	33,500
Mud Creek	British Columbia	4.1	480	1025	Silt loam	17,600
Rover-Sedlack	British Columbia	6.7	843	835	Fine sandy loam	36,300
Council	Idaho	8.5	904	1575	Loamy-skeletal	25,000
Fall River	Washington	8.2	2234	334	Silt loam	39,000
Diamond Lake	Oregon	9.2	1329	862	Sandy loam	12,500

*Air and precipitation averages are from Climate NA_Map modeled for each location for the decade of 2001–2010 (Wang et al. 2016).
[§]Amount of forest floor removed in the OM_2 treatment.

study: 2 species × 1 replicate × 5 treatments × 2 subplots × 25 stakes.

2.3.2. United States

Council – The Council LTSP site is located in central Idaho on the Payette National Forest, and has the highest elevation, steepest slopes, and lowest precipitation of all study sites (Table 1). This site is on a south-facing slope with a mixed conifer overstory of Douglas-fir, grand fir (*Abies grandis* (Douglas. ex. D.Don.) Lindl.), and ponderosa pine. Approximately 80% of the precipitation falls as snow and there is a prolonged summer drought. The soil series is a Klicker silt loam, which was formed from basalt and loess colluvium mixed with volcanic ash and is underlain with a very cobbly silty clay loam. It is classified as loamy-skeletal, mixed, superactive, mesic Vitrandic Argixerolls (Soil Survey Staff, 2009). The site was clearcut-harvested and LTSP treatments established in 1994. In June 2001 we established wood stake plots in two replicates of the C_0OM_0, C_0OM_2, C_2OM_0, C_2OM_2 treatments and in an adjacent unharvested stand. A total 1000 wood stakes were placed into the mineral soil of each plot: 2 species × 2 replicates × 5 treatments × 2 subplots × 25 stakes.

Fall River – The Fall River affiliate site is located in the Coastal Range of Washington State approximately 60 km southwest of Olympia and had a Douglas-fir and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) overstory. The climate is maritime with wet, mild winters and warm, dry summers (Ares et al., 2007). It is the wettest of our study sites, receiving approximately 2300 mm of precipitation, mostly as rain, but summers are dry, averaging 240 mm of rain from June through September (Ares et al., 2007). The soil developed from weathered Miocene basalt (Boistfort silt loam) but has a volcanic ash component from the eruption of Mt. Mazama (~6850 years B.P.). It is classified as medial over clayey, ferrihydritic over parasesquic, mesic Typic Fulvudand with a slope < 10% (Soil Survey Staff, 2009).

The site was clearcut-harvested in 1999, and we used the two OM removal treatments (OM_0, OM_2) on 4 replicates in our study. The OM_2 treatment removed logging residue from the whole-tree harvest and any legacy wood material, but not the surface organic layer. Trees were directionally hand-felled so that the tops remained within the plots, and logs were removed by cable to minimize soil compaction. In the soil compaction plots, trees were yarded with a CAT 330L shovel with 70-cm wide pads. Eight traffic lanes were established within each compacted plot, and every other lane was used twice to simulate harvesting patterns (Ares et al., 2005). However, the compaction treatment only occurred in the OM_0 treatment, so stakes were placed in the equipment tracks to establish the C_2OM_0 treatment for our decomposition study. In June 2001 we established one plot in the C_0OM_0, C_0OM_2, and C_2OM_0 treatment in each of the four replicates and in an adjacent unharvested stand, and inserted 800 stakes into the mineral soil on this study site: 2 species × 4 replicates × 4 treatments × 25 stakes.

Diamond Lake – This study site is dominated by Douglas-fir and is located on the Umpqua National Forest in southern Oregon. The soil series is a Freezener gravelly loam derived from pumice deposition during the Mt. Mazama eruption, and classified as a fine, mixed, superactive, mesic Ultic Haploxeralf. This soil is well drained and usually moist, except for 60–90 days during the summer (Soil Survey Staff, 2009). The site was clearcut-harvested in the winter of 1996 using directional falling to limit soil impacts, and three replicates of the C_0OM_0, C_0OM_2, C_2OM_0, C_2OM_2 LTSP treatments were established in 1997. In May 2001 we placed 1500 wood stakes into the mineral soil of two subplots in one plot of each LTSP treatment replicate and in the adjacent unharvested control stand: 2 species × 3 replicates × 5 treatments × 2 subplots × 25 stakes.

2.4. Soil sampling and characterization

During stake installation, soil bulk density cores were collected at 10 cm depth-intervals with a slide hammer coring system, and average total bulk density (uncorrected for rock-fragment content) of the unharvested, C_0, and C_2 plots is presented in Table 2. Once dried, samples were sieved (<2 mm) and processed for OM content by loss-on-ignition and soil pH on a 2:1 water-soil paste. Soil temperature sensors (Hobo MX2303 external temperature sensor and data logger, Onset Computer Corp., Bourne, MA) were placed in 1 replicate of each LTSP treatment at each site. Table 3 summarizes average soil temperature and sensor depth for 2 growing seasons (April-October) during the study; except for Rover-Sedlack where data were available for 2008–2010. We also tried to collect soil moisture information, but these data were generally not complete across all sites, except from Fall River. Additional Fall River soil temperature and moisture data can be found in Ares et al. (2007).

2.5. Data analysis

Analyses were conducted using SAS version 9.4 (SAS Institute, Cary, NC) and assessed at the $\alpha = 0.05$ significance level. The five stakes removed from each subplot at each sample date were analyzed for weight loss and the results averaged before analysis. Only this average was used as an observation for each treatment in the statistical analyses. SAS PROC GLM was used to conduct an analysis of variance (ANOVA). Factors in this analysis were site, stake species, treatment, and extraction date. The response variable was stake mass loss as a proportion of the original mass, and each factor and all possible interactions were considered in the model. *Post hoc* assessments of significant effects and interactions were conducted with SAS PROC MEANS using Tukey's range test. Differences in stake moisture contents were compared with two-sample t-tests using SAS PROC TTEST with results considered for either pooled or un-pooled variance as indicated by preliminary F-tests for homogeneity of variance. Pearson correlation coefficients were generated utilizing SAS PROC CORR for stake water: stake mass loss relationships.

3. Results

As shown in Table 4, the ANOVA model indicated the strong impact of tree species (aspen or pine) on wood stake mass loss, as the explanatory power of stake species ($F = 84.9$) was large, which may confound the separation of the LTSP treatment effects in the model. Therefore, our wood stake decomposition results were analyzed separately by stake species. Separate models, while still statistically valid, reduce the overall power of the test, but increase the clarity of the LTSP treatments and study site effects. Treatment plots in British Columbia were installed later than those in the United States and had only one replicate, which could impact the soil treatment * site interaction ($p \leq 0.0001$) when compared the LTSP site in the United States, which had 3 or 4 treatment replicates. Therefore, the British Columbia and United States sites were analyzed separately.

3.1. Mass loss

3.1.1. British Columbia

In contrast to our hypotheses, there were no significant effects of the LTSP treatments compared to the control on aspen stake mass loss after three growing seasons at the four study sites (Table 5). However, the rehabilitation of compacted soil at all sites increased wood decomposition. Aspen mass loss in each LTSP soil treatment was not significantly different when compared across the four study sites, except for a greater impact of the rehabilitation treatment on the Kootenay East as compared to the C_0OM_0 and unharvested control soil. At Mud Creek the rehabilitation treatment had significantly greater mass loss than only the unharvested control.

Similar to aspen decomposition, the timber harvest and subsequent LTSP treatments had little effect on pine mass loss in the mineral soil after three growing seasons (Table 5). However, in contrast to aspen decomposition, pine stake mass loss across study sites was significantly

Table 2
Wood stake installation date and average selected soil properties for each Long-Term Soil Productivity wood stake study site and treatment plots. Sampling depth in British Columbia was 0–20 cm and 0–30 cm in the United States. Bulk density values are an average of all OM treatments. Organic matter, rocks, and pH are averaged across all treatments. Stakes were installed in the spring (April -June).

Site	Stake installation date	OM(%)	Rock fragments > 2 mm(%)	pH	Bulk Density (Mg m^{-3})			
					Unharvested Control	C_0	C_2	Rehab
British Columbia								
Emily Creek	2002	4.2	10–25	6.1	1.11	1.21	1.74	0.85
Kootenay East	2002	6.1	10–25	6.9	1.01	1.12	1.42	1.10
Mud Creek	2001	5.5	10–15	7.0	1.13	1.17	1.51	0.92
Rover-Sedlack	2002	3.2	0–30	5.7	1.13	1.18	1.30	0.90
United States								
Council	2001	8.4	12	4.9	0.78	0.84	1.07	–
Fall River	2000	15.1	<1	5.2	0.63	0.63	0.82	–
Diamond Lake	2001	4.3	15	5.9	0.68	0.66	0.85	–

Note: Soil data for the British Columbia sites is from Berch et al. (2019) and from Ares et al. (2007) for the Fall River site. Council and Diamond Lake data are unpublished.

Table 3
Average growing season (April-October) soil temperature from available depths for British Columbia and United States Long-Term Soil Productivity treatment plots and the unharvested control.

Site	Temperature sensor depth	LTSP treatment				Unharvested Control
		C_0OM_0	C_0OM_2	C_2OM_0	C_2OM_2	
	cm	Soil temperature (°C)				
British Columbia						
Emily Creek	20	10.5	–	–	–	–
Kootenay East	20	12.2	–	–	–	–
Mud Creek	10	11.3	11.8	11.5	11.9	11.3
Rover-Sedlack	20	12.7	–	–	–	–
United States						
Council	15	13.6	15.9	16.0	16.9	10.3
Fall River	20	11.1	12.7	8.2	–	9.4
Diamond Lake	20	13.0	13.1	14.4	14.0	9.1

Note: Additional soil temperature data can be found in Terry and Ares (2007) for Fall River and Tan et al. (2007) for Mud Creek.

Table 4
Full model ANOVA main effects of with wood stake mass loss as the dependent factor and wood stake, site, and treatment as the independent factors.

Factor	Degrees of Freedom	F	P
Species	1	84.9	≤ 0.0001
Site	6	15.6	≤ 0.0001
Treatment	5	15.0	≤ 0.0001

different in three of the four LTSP treatments, with decomposition being least affected in the Emily Creek and East Kootenay soil. The impact of the soil rehabilitation treatment on pine decomposition was greater at Kootenay East. Surprisingly, there was little difference between pine and aspen stake mass loss in the LTSP treatment plots and in the unharvested soils. However, when the mass loss of each species was averaged across the four LTSP treatments and the unharvested control, aspen stake decomposition was significantly higher than pine in the Emily Creek, East Kootenay, and Mudd Creek soil ($p \leq 0.0001$), but not at Rover-Sedlack ($p = 0.8030$). Furthermore, aspen stakes in the C_2OM_2 and all

Table 5
Mass loss and standard error (±SE) of aspen and pine stakes after three-years in the mineral soil of LTSP study sites in British Columbia. Within each site (rows) the lowercase letters (a, b, c) indicate significant ($\alpha = 0.05$) differences among treatments. Within each stake species (aspen or pine) and treatment (columns), uppercase letters (X, Y, Z) indicate significant ($\alpha = 0.05$) differences among sites. *Aspen mass loss is significantly higher than pine mass loss for individual treatments at each site ($\alpha = 0.05$).

Site	LTSP Treatment				Unharvested Control	Rehab
	C_0OM_0	C_0OM_2	C_2OM_0	C_2OM_2		
	Stake mass loss (%)					
Aspen						
Emily Creek	54.6 (9.1)	–	50.7 (7.2)	69.2 (6.8)	–	67.8 (5.5)^{Y*}
Kootenay East	37.6 (7.3)^{b}	60.8 (4.8)^{ab}	54.2(8.0)^{b}	58.7(6.4)^{b*}	35.9 (7.1)^{b}	86.7(4.5)^{aX*}
Mud Creek	51.8 (5.6)^{ab}	65.0 (3.8)^{ab}	55.4 (6.1)^{ab}	54.6 (3.3)^{ab}	34.6 (6.1)^{b}	67.5 (2.5)^{aY*}
Rover-Sedlack	–	64.5 (4.3)	46.1 (0.9)	63.2 (5.9)	56.9 (11.4)	54.2 (4.2)^{Y*}
Pine						
Emily Creek	34.5 (5.8)^{XY}	–	28.8 (9.4)	47.8 (8.0)^{XY}	–	36.6 (5.4)
Kootenay East	16.5 (7.4)^{Y}	47.8 (5.3)^{Y}	41.0 (7.1)	35.4 (7.8)^{Y}	29.4 (8.9)^{Y}	44.4 (14.0)
Mud Creek	53.1 (4.6)^{abX}	65.4 (3.0)^{aX}	41.3(6.7)^{bc}	54.3 (2.9)^{abXY}	22.6 (5.3)^{cY}	39.8 (3.9)^{bc}
Rover-Sedlack	–	60.7 (3.0)^{aXY}	46.4 (19.4)^{ab}	70.5 (7.4)^{aX}	65.1 (2.1)^{abX}	35.3 (6.3)^{b}

the rehabilitation plots were significantly greater than pine stakes.

3.1.2. United States

In contrast to the results on the British Columbia study sites, the LTSP compaction increased mineral soil aspen stake decomposition on two of the three U.S. sites (Diamond Lake and Council), but surface OM removal had no effect at all three sites (Table 6). Aspen mass loss was highest in the compacted soil with surface litter (C_2OM_0) and decreased where the litter layer was removed (C_2OM_2), especially at Diamond Lake. When the LTSP treatments were compared across the three study sites, aspen mass loss was lowest in C_2OM_0 and C_0OM_2 plots at the Fall River site. The clearcut harvest also increased aspen stake decomposition, which did not occur at the British Columbia sites.

At the end of three growing seasons the pattern of pine decomposition in the LTSP study plots was similar to aspen (Table 6). Pine stake mass loss was highest in the compacted C_2OM_0 soil treatment at Diamond Lake and Council, but the removal of surface OM did not affect decomposition. The clearcut harvests also decreased pine stake mass loss. Comparing decomposition across study sites, pine stake mass loss was more rapid in the C_0OM_2 and C_2OM_0 treatments, especially in the Diamond Lake soil. Contrary to the British Columbia results, pine stake mass loss was significantly lower than aspen in several LTSP soil treatments at the Diamond Lake and Council sites. The difference between pine and aspen mass loss on each LTSP treatment at Fall River was not significant, but when averaged across treatments, pine stakes decomposed slower than aspen ($p = 0.0009$). Pine stake decomposition was also slower in the mineral soil of the three uncut control stands.

3.2. Water content

As noted earlier, suitable mineral soil moisture data was unavailable on many of the LTSP treatments in both British Columbia and the United States. However, due to slow changes in water content of stake-sized wood pieces in mineral soil after normal precipitation events (Matthews, 2014), the water content of our stakes would be an indicator of soil water conditions for an extended time period before the extraction date.

The LTSP treatments at the British Columbia study sites had relatively little effect on the water content of both aspen and pine stakes, except at Rover-Sedlack (Table 7). Stake water content of both species were higher in the rehabilitated soils at Mudd Creek, East Kootenay, and Rover-Sedlack and generally lower in the unharvested control stands. In addition, stake water content in the C_0OM_2 plot at Rover-Sedlack was significantly greater than the other two LTSP treatments and the unharvested control. In the United States, the water content of aspen and pine stakes also showed few differences among LTSP treatments at each of the three sites (Table 8). Again, the water content of aspen and pine stakes showed the same general pattern as mass loss, and when averaged across all treatments, both were positively correlated with stake mass loss at all sites.

Table 6
Mass loss and standard error (±SE) of aspen and pine stakes after three-years in the mineral soil of LTSP study sites in the United States. Within each site (rows) the lowercase letters (a, b, c) indicate significant ($\alpha \leq 0.05$) differences among treatments. Within each stake species (aspen or pine) and treatment (columns), uppercase letters (X, Y, Z) indicate significant ($\alpha = 0.05$) differences among sites. *Aspen mass loss is significantly higher than pine mass loss for individual treatments at each site ($\alpha = 0.05$)

Site	LTSP Treatment				Unharvested Control
	C_0OM_0	C_0OM_2	C_2OM_0	C_2OM_2	
	Stake mass loss (%)				
Aspen					
Council	49.7 (6.2)^{a*}	49.0 (3.1)^{aXY}	68.7 (3.1)^{bX*}	59.4 (6.4)^{ab}	27.8 (4.9)^{c*}
Fall River	39.4 (2.9)	39.3 (3.1)^{Y}	32.5 (2.7)^{Y}	–	29.0 (2.6)*
Diamond Lake	53.7 (4.4)^{b}	52.6 (4.6)^{bX*}	73.2 (4.8)^{aX*}	44.1 (5.8)^{bc}	35.7 (3.2)^{c}
Pine					
Council	26.4 (4.6)^{bY}	36.0 (5.9)^{ab}	51.4 (5.9)^{aX}	41.6 (7.0)^{ab}	24.2(6.1)^{c}
Fall River	31.8 (3.5)^{aXY}	34.2 (2.9)^{a}	28.3 (2.4)^{abY}	–	19.6 (2.8)^{b}
Diamond Lake	45.8 (4.4)^{abX}	38.8 (3.4)^{ab}	54.4 (3.8)^{aX}	34.9 (6.3)^{ab}	22.4 (3.6)^{b}

3.3. Climate gradient

In contrast to our hypothesis, wood stake mass loss along the climatic gradient from southern British Columbia to southern Oregon did not show a trend of increasing decomposition with increasing temperatures (Table 9). When averaged across LTSP treatments and uncut controls, stake water contents at Fall River were significantly higher than all seven study sites and had the lowest mass loss after three growing seasons. The high rainfall amounts at this site are likely the reason for these two trends. Diamond Lake, the southernmost and warmest site that receives over 1200 mm of rainfall, had less aspen and pine mass loss and water content than the more northern Rover-Sedlack site, which is cooler and drier (Table 1).

4. Discussion

4.1. Soil compaction

The LTSP study was established to systematically evaluate how surface OM removal and soil compaction would affect a variety of site processes (Powers et al., 2005). We hypothesized that both of these treatments, plus the environmental gradient would likely affect wood decomposition by altering soil water contents, gas exchange, nutrient availability, and temperature. In our study we used wood stakes to compare the effect of soil compaction and surface OM removal on wood decomposition in the mineral soil.

The effect of the compaction treatment on soil bulk density was still evident when our wood stakes were installed (Table 2), but to our surprise, it had relatively little effect on wood stake decomposition, and was inconsistent among treatments when significant mass loss differences were present. Contrary to our hypothesis, soil compaction increased aspen and pine decomposition at Council and Diamond Lake and had little impact at the other sites. However, increased stake decomposition after rehabilitation of compacted soil on several British Columbia sites reflects the effect of lowering soil bulk density with mechanical tillage and the incorporation of surface OM into the mineral soil. Rehabilitation of compaction with OM incorporation may have contributed to additional soil warming, added a food source for microbes, increased soil water, altered N transformation rates and soil respiration (Tan et al., 2005) or reduced N leaching (Strahm et al., 2005), particularly early in stand development after harvesting. The compaction of the sandy surface soil at Rover-Sedlack and the pumice soil at Diamond Lake likely altered pore size distributions that increased water-holding capacity (Siegel-Issem et al., 2005). Other studies have reported the effects of increased soil bulk density on altering respiration and N-mineralization rates (Jensen et al., 1996; Beylich et al., 2010).

4.2. Soil OM removal

Contrary to our 2nd hypothesis, the removal of surface OM had almost no effect on the decomposition of wood stakes at any of the seven LTSP study sites. Few studies have examined wood decomposition in the mineral soil as affected by surface OM retention or removal after harvesting (Jurgensen et al., 2006). However, there is an indication that OM retention can affect microbial community function or structure

Table 7
Water content (%) dry weight of aspen and pine stakes in the mineral soil of the British Columbia LTSP study sites. Within each site (rows), lowercase letters indicate significant ($\alpha \le 0.05$) differences among treatments.

Site	LTSP Treatment				Unharvested control	Rehab	Correlation with mass loss*
	C_0OM_0	C_0OM_2	C_2OM_0	C_2OM_2			
	Stake water content (%)						
Aspen							
Emily Creek	80.9	–	85.8	98.3	–	83.5	0.498
Kootenay East	81.6^{b}	79.9^{b}	100.4^{a}	83.0^{b}	60.8^{c}	129.6^{a}	0.791
Mud Creek	92.5^{ab}	85.8^{b}	74.6^{bc}	76.5^{b}	70.2^{c}	114.5^{a}	0.630
Rover-Sedlack	–	155.1^{a}	71.7^{c}	109.0^{b}	70.9^{c}	121.0^{ab}	0.602
Pine							
Emily Creek	74.8^{a}	–	67.7^{ab}	80.0^{a}	–	55.4^{b}	0.558
Kootenay East	67.7^{b}	84.0^{ab}	89.3^{ab}	87.5^{ab}	61.1^{b}	101.2^{a}	0.808
Mud Creek	99.3^{a}	98.1^{a}	69.7^{b}	89.0^{ab}	55.0^{c}	107.4^{a}	0.537
Rover-Sedlack	–	100.4^{a}	61.2^{b}	110.5^{a}	71.9^{b}	74.4^{b}	0.793

*Stake water content dry weight is an average across all treatments and all mass loss correlations were significant to p = 0.0010.

Table 8
Water content (%) dry weight of aspen and pine stakes in the mineral soil in the United States LTSP study sites averaged over three growing seasons. Within each site (rows), lowercase letters indicate significant ($\alpha \le 0.05$) differences among treatments.

Site	LTSP Treatment				Unharvested Control	Correlation with mass loss*
	C_0OM_0	C_0OM_2	C_2OM_0	C_2OM_2		
	Stake water content (%)					
Aspen						
Council	92.5^{bc}	98.0^{b}	115.6^{a}	99.1^{ab}	81.8^{c}	0.580
Fall River	210.5^{a}	168.8^{b}	166.2^{b}	–	116.5^{c}	0.418
Diamond Lake	111.2^{ab}	94.3^{b}	123.2^{a}	65.6^{c}	64.9^{c}	0.466
Pine						
Council	67.6^{bc}	63.2^{c}	82.2^{a}	78.5^{ab}	62.7^{c}	0.668
Fall River	131.1^{a}	133.2^{a}	119.9^{a}	–	68.4^{b}	0.646
Diamond Lake	75.6^{a}	52.4^{b}	85.9^{a}	52.5^{b}	57.0^{b}	0.644

*Stake water content dry weight is an average across all treatments and all mass loss correlations were significant to p = 0.0010.

Table 9
Overall wood stake mass loss (%), water content (%) dry weight and average annual air temperature and precipitation from local weather stations across the LTSP study sites in British Columbia and the western United States. Within each mass loss and water content column different letters indicate significant ($\alpha = 0.05$) differences among site.

Site	Aspen		Pine		Temperature	Precipitation
	Mass loss	Water Content	Mass loss	Water content		
	Percent (%)				°C	mm
British Columbia						
Emily Creek	58.2^{a}	88.3^{cd}	37.0^{c}	74.0^{c}	3.7	513
Kootenay East	49.4^{b}	80.3^{d}	34.0^{c}	78.1^{c}	3.9	479
Mud Creek	52.3^{ab}	80.4^{d}	47.3^{b}	81.6^{bc}	4.4	455
Rover-Sedlack	57.7^{a}	114.2^{b}	60.7^{a}	94.1^{b}	6.7	843
United States						
Council	50.9^{b}	95.8^{c}	35.9^{c}	69.0^{cd}	8.5	250
Fall River	35.0^{c}	165.7^{a}	28.5^{d}	112.2^{a}	9.2	2300
Diamond Lake	51.9^{ab}	88.6^{cd}	39.3^{bc}	63.2^{d}	10.0	1216

(Hannam et al., 2006; Allmér et al., 2009). Mycorrhizal and saprobic fungi may be the organisms most susceptible to surface OM losses (Berch et al., 2011; Hartmann et al., 2012), which may alter belowground processes and wood decomposition rates. On 18 LTSP sites across North America, loss of surface OM (with no compaction) affected microbial communities when measured 11 and 17 years after plot installation (Wilhelm et al., 2017). Fifteen years after OM and compaction treatments were established on the three subboreal spruce and three interior Douglas-fir LTSP sites in British Columbia, Hartmann et al. (2012) reported that clearcut harvesting impacts were greater than the individual LTSP treatments, but both soil compaction and OM removal resulted in distinct microbial communities within treated plots. This result is similar to three other LTSP sites across North America, which indicated that after five years community structure was altered more by the harvest than the LTSP treatments (Busse et al., 2006). Microbial communities may have some level of functional redundancy (Hartmann et al. 2012), so the impacts on wood decay may be minimal when we conducted this study, but it is important to continue monitoring ecosystem changes on the LTSP plots.

In British Columbia, uniform white birch (*Betula pendula* Roth) tongue depressors were used in LTSP mini-plots adjacent to the main LTSP treatments to assess OM decomposition for the first three years after site establishment (Norris et al., 2015). Because of high variability, the data was combined by treatment and year so only site data is available for this study and shows that mass loss was greater at Kootenay East as compared to Emily Creek for the interior Douglas-fir plots, but Rover-Sedlack had the greatest overall mass loss. For our wood stakes, Emily Creek had greater aspen mass loss than at Kootenay East, which may be a function of when the wood stakes were installed or type of soil. However, Ponder et al. (2017) reported that OM removal resulted in negligible changes in mass loss of buried northern red oak (*Quercus rubra* L.) and white oak (*Quercus alba* L.) wood stakes in a regenerating mixed-oak LTSP study site in Missouri.

4.3. Climate effects

The lack of detailed soil moisture and temperature information greatly impaired our ability to assess the effect of these important climatic variables on wood stake decomposition among the different LTSP soil treatments and among the seven study sites. Diamond Lake had the warmest average air temperature (Table 1) and Council has south-facing slopes which, when combined with hot, dry summers, likely contributed to warmer soil temperatures during the growing season (Table 3), but the overall changes in mass loss over three years was less than at Rover-Sedlack (Table 9). Significant site differences are likely due to a combination of soil texture, pH, annual precipitation amounts (Table 1), soil temperature (Table 3), or reduced levels of evaporation (mulch effect). For example, Rover-Sedlack had lower pH as compared to the other British Columbia sites, which was likely more favorable for fungal decay (Hietala et al. 2016). Further, compaction at Diamond Lake (pumice soil) contributed to increased stake water content by altering soil pore space and, when combined with retention of surface OM, increased stake mass loss.

Because of its geographic location (Fig. 1), Fall River had fewer extreme temperature days as compared to the inland sites and, therefore we did not expect it to have such low decay rates in comparison to the other sites because of the maritime influence of year-round temperatures above freezing. However, this site receives the greatest amount of precipitation and, when digging up wood stakes from this site, we noted that soil around the stakes was often mottled and gleyed, indicating low oxygen conditions. We also noted that our wood stakes were soft but did not exhibit fungal white or brown rot (Blanchette 1984). Under anaerobic soil conditions bacterial degradation of the wood stakes may have been occurring, but this process is generally slower than fungal decay (Johnston et al., 2016; Elam and Björdal, 2020). In addition, wood blocks at high moisture contents (95% of wood water holding capacity) had lower mass loss as compared to blocks with lower moisture contents (Marais et al., 2020). Depending on the length of wood saturation and number of alternate cycles of aerobic and anaerobic conditions, microbial decay can be inhibited or promoted (Reddy and Patrick, 1975; Marais et al., 2020). Therefore, on-site measurements of temperature and precipitation are needed to better assess the factors controlling OM decomposition in the mineral soil, especially after soil disturbance.

Wood decomposition is affected by the decomposer community (Stenlid et al., 2008), but soil temperature (Kirschbaum, 1995), local precipitation rates and timing (Berg et al. 1993; Harmon et al. 1986), and evaporation (soil drying) may also determine soil biotic activity (A'Bear et al., 2013). We show that wood water content, and therefore soil moisture, is an important driver of mass loss. However, better understanding soil microsite and climatic variability will shed light on the longevity of coarse roots (which the stakes simulate) in the mineral soil. Changes in fungal and bacterial diversity may also be related to site biogeoclimatic conditions associated with OM removal that altered fungal populations (Wilhelm et al., 2017). For example, in British Columbia the more acidic soil at Rover-Sedlack may have resulted in different fungal groups than on the more calcareous soils of Emily Creek, Mud Creek, and Kootenay East (Hietala et al., 2016). As pointed out by Bradford et al. (2014), site-specific environmental relationships likely drive the rates of wood decay in the mineral soil, but decay organisms are also affected by soil properties (Brischke et al., 2006).

4.4. Wood species

We expected faster decomposition of aspen and compared to pine, as has been shown in other wood stake studies (*e.g.,* Jurgensen et al. 2006; Page-Dumroese et al., 2019; Wang et al., 2018), primarily because angiosperm wood C:N ratio and other chemical properties (*e.g.,* lignin, cellulose) generally results in faster wood decay as compared to gymnosperms especially on common sites (Weedon et al., 2008). In addition, the quality of the wood substrate (Hu et al. 2018; Wang et al., 2018) and the associated microbial biodiversity (Wilhelm et al., 2017; Wang et al., 2020) likely alter wood stake mass loss at each site. However, on several sites and LTSP treatments, this difference was not significant (Table 5 and Table 6). In addition to altering soil environmental and chemical conditions (*e.g.,* OM content, pH), residue retention and removal can alter microbial biodiversity (Nordén et al., 2004; Verschuyl et al., 2011), which may also alter decomposition rates among species within a plot.

5. Management implications

1. Previous studies have suggested that the microbial community is resilient to soil compaction (Busse et al., 2006), but longer-term microbial data indicates that compaction may be detrimental to microbial community structure and function and therefore, to decomposition processes (Hartmann et al. 2012; Wilhelm et al., 2017). Soil changes associated with compaction on LTSP sites have shown no effect (Sanchez et al., 2006) or increases (Tan et al., 2005) in total N and P contents which may (Li et al., 2003) or may not (Tan et al., 2005) reduce N mineralization rates and subsequently influence wood decomposition. However, changes in soil environmental conditions (*e.g.,* water movement, soil gases) and the longevity of compaction at depth on some sites (Powers et al., 2005) may indicate that the potential for long-term impacts are possible. Therefore, it is still prudent to understand how soil texture and compaction are related to microbial processes on given sites and to avoid large-scale increases in soil bulk density.
2. After three growing seasons, OM removal had little effect on wood stake decomposition in the mineral soil. However, longer-term microbial studies on LTSP study plots indicates there can be a significant alteration in community structure and function which may affect long-term wood decay processes (Wilhelm et al., 2017). Surface OM provides protection from erosion, evaporation, overland flow, and ensures microbial functions. Management practices such as scalping, putting a bulldozer blade down while traversing a site, or moving surface OM into burn piles may all change decay processes in the mineral soil, alter carbon, and change how microbial communities respond to harvesting. However, the importance of OM horizon retention to nutrient cycling and water retention indicates a need to conserve these horizons on many forest sites.
3. Clearcutting has been shown to have large effects on soil decomposition processes and fungal community composition (Kohout et al., 2018). Aspen and pine stake mass loss in the unharvested stands was generally slower and the stakes drier than in the treated plots. This same trend in stake mass loss differences between the unharvested and cut stands was noted in other wood stake decomposition studies (*e.g.,* Finér et al., 2016; Wang et al., 2018; Page-Dumroese et al., 2019) that found a strong influence of canopy coverage on stake mass loss in the mineral soil. In contrast, litter decomposition in clearcut stands in British Columbia was either slower or the same as in forested stands (Prescott et al., 2004). The difference between surface litter mass loss and mineral soil wood stake mass loss is likely related to surface drying during snow-free periods, increased daytime temperature, and wind movement across the soil surface, which slows decomposition (Prescott et al., 2004; Yin et al., 1989). Clearcut-harvesting results in many soil changes (*e.g.,* more precipitation reaching the soil, greater temperature fluxes) while unharvested stands generally have cooler temperatures, greater

evapotranspiration, less volumetric soil moisture, lower soil bulk densities, and have an intact forest floor. As climates change, understanding baseline levels of belowground processes is critical for also understanding the decomposition of recalcitrant OM pools.

The use of wood stakes as an index of OM decomposition matched previous studies, which indicated greater mass loss following harvest operations as compared to unharvested stands due to changes in both moisture and temperature regimes. However, differences in stake mass loss rates among LTSP treatments at a site were not as expected. For example, stakes in the rehabilitation plots had relatively high water contents and mass loss, suggesting a restoration of biological activity in the most severe compaction treatment and perhaps, higher long-term soil productivity. Therefore, the next step will be to compare treatment tree growth rate differences at each study site, and assess if there is any relationship to soil OM decomposition, as indicated by wood stake mass loss.

CRediT authorship contribution statement

Deborah S. Page-Dumroese: Conceptualization, Validation, Investigation, Writing - original draft. **Martin F. Jurgensen:** Conceptualization, Validation, Writing - review & editing. **Chris A. Miller:** Validation, Formal analysis, Writing - review & editing. **Matt D. Busse:** Validation, Investigation, Writing - review & editing. **Michael P. Curran:** Validation, Investigation, Writing - review & editing. **Thomas A. Terry:** Validation, Investigation, Writing - review & editing. **Joanne M. Tirocke:** Validation, Investigation, Writing - review & editing. **James G. Archuleta:** Investigation, Writing - review & editing. **Michael Murray:** 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.

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