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Fungal inoculations and mechanical wounding of trees have limited efficacy for snag creation two decades after treatment

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ABSTRACT

Standing dead trees (snags) support multiple functions within forest ecosystems by providing vertical structure, contributing to nutrient flows and carbon cycling, and serving as habitat elements for a diversity of organisms. In many forest landscapes, managers often use snag creation to enhance structural diversity, particularly in areas where snag loss is high and natural snag recruitment is low. Despite snag creation being used across a range of forest types on both private and public lands, a dearth of long-term studies has led to uncertainty about which techniques work best to create snags and support deadwood-dependent organisms over long (>15 y) timescales. In this study, I assessed the long-term consequences of varied snag creation treatments applied to live Douglas-fir (*Pseudotsuga menziesii*) trees in two study areas near Coos Bay, in southwestern Oregon, USA. Treatments included chainsaw topping, fungal inoculation, topping + inoculation, and mechanical wounding at the base. Trees were revisited 18–20 y after treatment and nearly all focal trees (97.6%, n = 809) remained standing when relocated. Markers of decay – including whether a tree was broken, cracked along the bole, had peeling bark, or harbored shelf fungi – were most pronounced on trees that had experienced one of two chainsaw topping treatments, differentiated by the number of retained branch whorls. In contrast, limited decay was observed on trees subjected to fungal inoculation and mechanical wounding treatments, likely due to the slow pace of decay processes in injured trees. The same pattern held for both bark cover and cavity cover, the latter an index of created snag use by woodpeckers, a keystone group within forest ecosystems. Finally, adding fungal inoculation to chainsaw topping of trees led to little additional decay relative to chainsaw topping alone. These findings indicate that managers should choose snag creation methods that align with the timeframe they require decaying trees to be available to deadwood-dependent organisms. They also show that combining different snag creation approaches that vary in timing of tree mortality and decay is likely to provide a longer window of use by wildlife and require lower implementation costs. Although snag creation is a widespread management tool, additional research is needed to ascertain the effectiveness of snag treatments across space and time, and to quantify the tradeoffs between the ecological benefits and financial costs that result from intentional snag creation.

1. Introduction

Standing dead trees (hereafter, snags) play many key roles in forest ecosystems because they contribute to carbon budgets and nutrient cycling, provide vertical structure, and act as habitat elements that support a wide range of deadwood-dependent organisms (Harmon et al., 1986; Hilger et al., 2012). For example, a substantial portion of vertebrate species within forests depend on snags for food, nesting cavities, and denning sites, including species of conservation concern (Bunnell et al., 2002; Martin et al., 2004; Drever et al., 2008). Previous investigations have demonstrated that many species of cavity-nesting birds use snags as foraging substrates, nesting sites, or both (Schreiber and DeCalesta, 1992; Chambers et al., 1997; Hallett et al., 2001; Walter and Maguire, 2005; Arnett et al., 2010). One group of primary cavity nesting birds, the woodpeckers (family Picidae), are of particular importance within forest landscapes because they act as ecosystem engineers through their foraging and nesting activities (Daily et al., 1993; Bednarz et al., 2004; Virkkala, 2006), enhance the breakdown of woody materials (Jackson and Jackson, 2004; Jusino et al., 2016), contribute to the population regulation of insect pests (Fayt et al., 2005), and serve as indicators of forest health (Drever et al., 2008). Thus, the maintenance of snags is of particular importance for supporting and sustaining forest biodiversity in a wide range of forest types.

Despite their ecological value, snags within managed forests are

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often removed for their commercial value or to avoid interference with forestry operations, especially in consideration of worker safety during timber harvest (Lewis, 1998; Lindenmayer and Noss, 2006; Kroll et al., 2012). These practices, combined with shortened harvest rotations in managed forests, have led to reductions in snag recruitment rates across forest landscapes, particularly for large-diameter snags (Rose et al., 2001; Huff and Bailey, 2009; Kroll et al., 2012). One option for mitigating snag loss and providing the habitat elements required by snag-dependent species is the intentional creation of snags, especially in conifer tree species. Historically, snags have been purposefully created from live trees by girdling, herbicide injection, explosives, and chainsaw topping, among others (Bull and Partridge, 1986; Lewis, 1998; Brandeis et al., 2002). Chainsaw topping is a widespread approach that uses tree climbing methods to remove the upper portion of a live tree and cause tree death (Bull and Partridge, 1986; Lewis, 1998). Chainsaw topping creates snags that typically persist longer and therefore have greater availability to snag-dependent species over time (Bull and Partridge, 1986), although not all topped trees undergo mortality (Huff and Bailey, 2009). Girdling can also be used to create snags and involves cutting through the bark and into phloem around the circumference of a tree to cause tree death via the disruption of nutrient transport pathways (Bull and Partridge, 1986; Kane et al., 2019). Relative to other snag creation methods, girdling may reduce the period that treated trees remain standing, depending on how girdling treatments are implemented (Bull and Partridge, 1986; Kane et al., 2019). Inoculating live trees with natural fungal pathogens can also be used to create snags, although the effectiveness of this approach can vary (Filip et al., 2011; Bednarz et al., 2013; Wainhouse and Boddy, 2022). Finally, mechanical wounding, which removes a section of the tree base (Lewis, 1998; Fig. 1) can be implemented for snag creation but is used less frequently than other

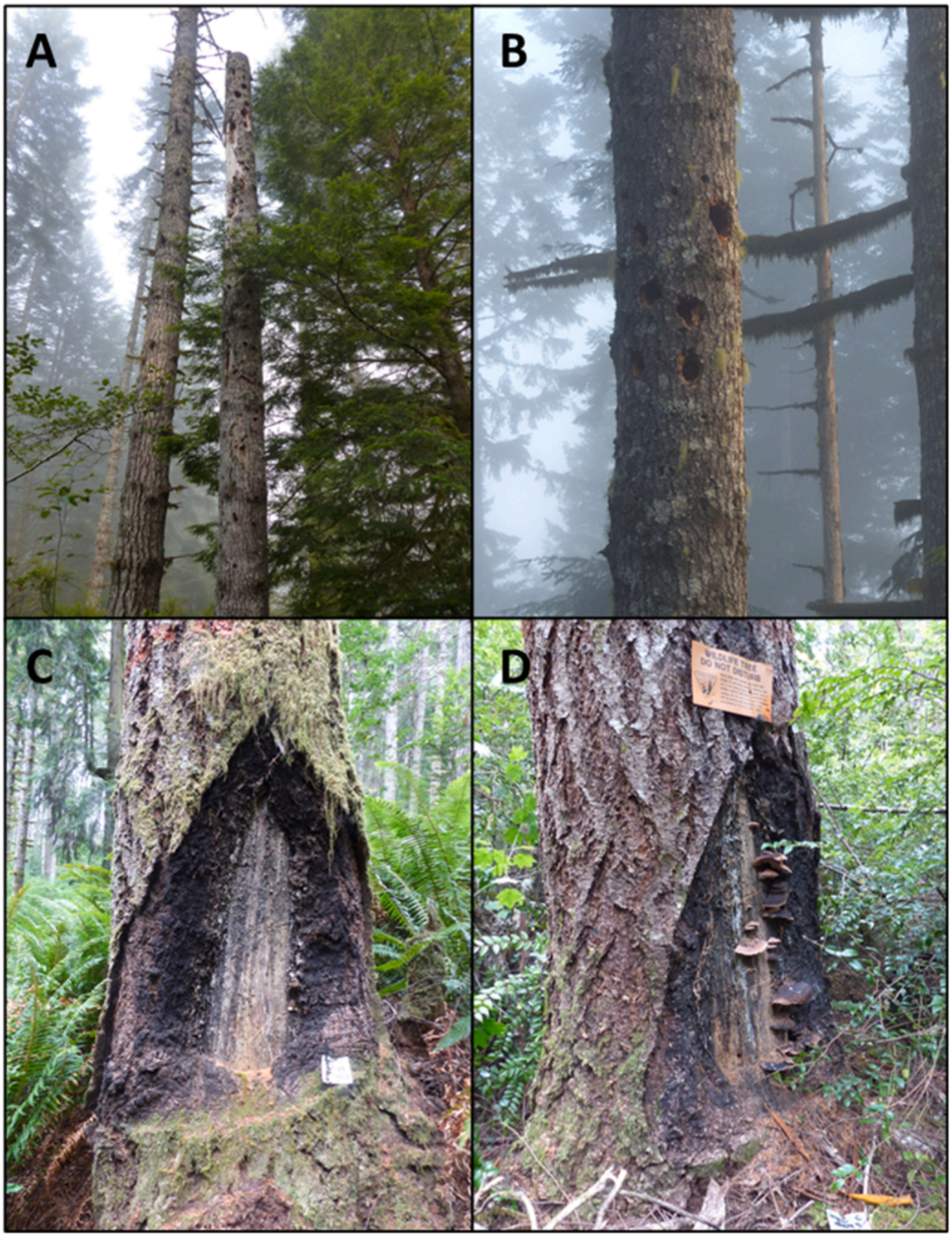

Fig. 1. Representative outcomes of two treatments evaluated 18–20 y after implementation in mature Douglas-fir forests in southwestern Oregon, USA. (A, B) Chainsaw topping typically leads to rapid tree mortality, as evidenced by the extensive decay and multiple cavities created by woodpeckers (family Picidae). (C, D) Mechanical wounding at the base causes slow decline of tree health and may promote hollows for wildlife over long timescales. Note the variation in fungal colonization between wounds in (C) and (D); the fruiting bodies in (D) are likely *Fomitopsis cajanderi* and indicate internal decay.

methods. In contrast to girdling, mechanical wounding is applied to only part of the circumference of a tree and therefore does not eliminate cambial transport. This leads to slower decline, reduces the likelihood of structural failure, and extends the timeframe over which decadent or dying trees are available to wildlife (Bull and Partridge, 1986; Shea et al., 2002; but see Brandeis et al., 2002; Kane et al., 2019). Because rates of decay and snagfall vary among snag creation treatments, forest managers may use a combination of methods to extend the functional lifespans of dead and declining trees in a particular area.

Although intentional creation of snags is practiced widely on private and public lands (Mannan et al., 1980; Bull and Partridge, 1986; Barry et al., 2018; Hane et al., 2019; Halpern et al., 2022), few studies have evaluated the efficacy of snag creation methods > 15 y after treatments were implemented (Barry et al., 2017, 2018; Kane et al., 2019). One exception found that $> 90\%$ of created Douglas-fir snags remained standing after 25–27 y (Barry et al., 2017) and many were used by cavity-nesting birds for foraging and nesting (Barry et al., 2018), although wildlife use decreased as snags aged (Chambers et al., 1997; Walter and Maguire, 2005). Nevertheless, the work undertaken by Barry et al., (2017, 2018) evaluated snags created by chainsaw topping and did not evaluate other treatment methods used by forest managers, such as mechanical damage or fungal inoculation (Bull and Partridge, 1986; Bednarz et al., 2013). Because snags can remain standing for > 100 y in unmanaged forests (Cline et al., 1980), information is needed regarding snag characteristics and the ecological benefits they provide from different snag creation methods over longer timeframes than is currently available.

In this study, I investigated tree decay characteristics and wildlife use of large-diameter Douglas-fir trees 18–20 y after they were subjected to chainsaw topping, fungal inoculation, and/or mechanical damage to the base. Trees were treated by the USDI Bureau of Land Management (BLM) as part of resource management planning actions with the goal of enhancing structural diversity for snag-dependent wildlife (Lewis, 1998). Specifically, I evaluated how snag creation treatments influenced tree-decay characteristics, including indices of snag use by primary cavity nesters (e.g., extent of cavity cover; Bednarz et al., 2013; Barry et al., 2017). I also tested several a priori hypotheses regarding two of the treatments used in this study to create snags and wildlife trees: chainsaw topping and fungal inoculation (Table 1). First, I evaluated whether decay characteristics increased with the extent to which live limbs were removed in conjunction with chainsaw topping of live trees, as whether a topped tree experiences mortality depends on the extent of intact live branches after topping (Bull and Partridge, 1986; Huff and Bailey, 2009). Second, I assessed whether combining fungal inoculations with chainsaw topping enhanced rates of tree decay. Finally, I examined whether mechanical wounding at the base led to decay characteristics that diverged from other treatments. Because there are few studies that evaluate the outcomes of different snag creation methods across long time intervals (Barry et al., 2017), this study provides a rare long-term evaluation of the efficacy of these management tools for providing structural diversity and promoting forest biodiversity. This is particularly true for fungal inoculation treatments because most prior studies have been of relatively short duration (< 10 y post-treatment; Brandeis et al., 2002; Filip et al., 2011; Bednarz et al., 2013) despite the slow pace of fungal development and associated decay (Lõhmus, 2016).

2. Materials and methods

2.1. Study area and experimental treatments

Treatments were implemented in two study areas – Steinnon Creek (43° 17’ N, 124° 05’ W) and Woodward Creek (43° 14’ N, 124° 05’ W) – both of which were located approximately 15 km southeast of Coos Bay, Oregon, USA on timberland managed by the BLM. The two study areas are approximately 4 km distant from each other and collectively cover ~7.5 km^2. In both locations, treatments were applied to late-seral stands (>80 y) within late successional reserves that were dominated by Douglas-fir (*Pseudotsuga menziesii*), and trees were treated in upland and riparian locations at least 10 m from stream channels. At the time of treatment, trees were uniquely marked with metal tags to aid with relocation, and GPS location, diameter at breast (DBH), and topping height (for trees that were topped) was recorded. In July 2001, a total of 161 live trees were treated at the Steinnon Creek study area using three treatments: (1) chainsaw topping at 24–30 m above ground leaving < 2 branch whorls (T1), (2) chainsaw topping at 24–30 m above ground leaving ≥ 2 branch whorls (T2), and (3) mechanical wounding at the base of ~ 1/3 of the tree’s circumference with a chainsaw (Wound; Fig. 1). In March-April 2003, 1022 live trees were treated at the Woodward Creek study area using the same treatments applied at Steinnon Creek, as well as three additional treatments that included fungal inoculation with *Phellinus pini*, a fungal pathogen that causes heart rot (Lõhmus, 2016) and is suitable for application to Douglas-fir in the study region (Filip et al., 2011). Those additional treatments included: (4) fungal inoculation with *Phellinus pini* (Inoc), (5) chainsaw topping at 24–30 m above ground leaving < 2 branch whorls + inoculation with *Phellinus pini* (T1 + Inoc), and (6) chainsaw topping at 24–30 m above ground leaving ≥ 2 branch whorls + inoculation with *Phellinus pini* (T2 + Inoc). All treatments using fungal inoculation were implemented in the same manner by first drilling a 2.2 cm wide hole that extended 13 cm into each tree’s bole and then inserting a 13 cm wooden dowel to which *P. pini* was applied; *P. pini* was cultivated from infected trees within the nearby Coquille River watershed, Oregon. Additionally, a 13 cm section of PVC pipe was tapped into the hole with approximately 10 cm of the pipe extending from the outer edge of the hole to prevent the wood from healing and for improved oxygen flow (Filip et al., 2011). Each tree that received fungal inoculation had three

Table 1
Description of the snag-creation treatments used in this study and predicted differences between treatments in tree decay. Because mechanical wounding is not typically used to create snags, there were no a priori hypotheses being tested relative to that treatment.

Treatment	Treatment abbreviation	Predicted differences in extent of tree decay	Rationale
Chainsaw topping[a] leaving < 2 branch whorls	T1	(a) T1 $>$ T2	Chainsaw topping of live trees does not always lead to tree mortality (Huff and Bailey, 2009) and removal of all live limbs in the crown leads to tree death (Bull and Partridge, 1986).
Chainsaw topping[a] leaving ≥ 2 branch whorls	T2	(b) T1_Inoc $>$ T1	Fungal pathogens serve as key mediators of the breakdown of woody materials within forest ecosystems (Lonsdale et al., 2008; Marcot, 2017).
Mechanical wounding with a chainsaw around ~ 1/3 of the base	Wound	(c) T2_Inoc $>$ T2	
Inoculation with *P. pini* only	Inoc	(d) T1_Inoc $>$ T2_Inoc	Chainsaw topping is more effective when fewer live branches remain (Bull and Partridge, 1986), and fungal pathogens drive wood decomposition in forests (Lonsdale et al., 2008; Marcot, 2017).
Chainsaw topping[a] leaving < 2 branch whorls + inoculation with *Phellinus pini*	T1_Inoc	(e) T1_Inoc $>$ Inoc	
Chainsaw topping[a] leaving ≥ 2 branch whorls + inoculation with *P. pini*	T2_Inoc	(f) T2_Inoc $>$ Inoc	

[a] Chainsaw topping of trees occurred 24.3–30.5 m above the ground.

holes drilled along the bole facing different aspects, with one hole made in each of the three recommended heights (Bednarz et al., 2013): low (6.1, 7.6, and 9.1 m above ground), medium (10.7, 12.2, and 13.7 m above ground), or high on the bole (15.2, 16.8, and 18.3 m above ground). For analysis, I did not consider the height at which fungal inoculation occurred to increase statistical power to detect treatment differences. Finally, only 21 (2.3%) of the 882 treated trees that the field crew initially searched for were created in a clumped pattern at the time of treatment, so I did not consider spatial aggregation in the analysis.

2.2. *Contemporary field surveys*

A field crew revisited a subsample of treated trees at both sites during September-November 2021 at 20 y and 18 y post-treatment at the Steinnon Creek and Woodward Creek study areas, respectively. At Steinnon Creek, as many trees were relocated as possible. At Woodward Creek, where the pool of trees was larger, trees were relocated at random to obtain 150 individuals in each of the three treatments shared between sites, and 80 in each of the three unique treatments. During fall 2021 field work, the following measurements were taken: tree status (standing/down), broken bole (yes/no), vertical cracks $\geq$ 2.5 cm in width on bole (yes/no), bark peeling on ≥ 1 m^2 of bole (yes/no), shelf fungus on bole (yes/no), bark cover (estimated to nearest 5%), cavity cover (estimated to nearest 5%), and tree decay class following Maser et al., 1979. If a treated tree was found to have fallen, field crews measured its fall orientation and characterized the snagfall as one of three types following the classification in (Rhoades et al., 2020,Bednarz et al., 2013,Barry et al., 2017,Barry et al., 2018). Finally, I note that although the response variables I measured ultimately originate from the same underlying decay processes within a tree, I considered them separately in my analysis because they represent outcomes that vary in their biological relevance. For example, bark peeling away from the bole can provide roosting habitat for bats (Arnett and Hayes, 2009; Fabianek et al., 2015) and nesting areas for the Brown Creeper (*Certhia americana*; Poulin et al., 2020), whereas a broken bole indicates a tree has died and is providing habitat elements on the ground for species that require down wood, such as terrestrial salamanders (Kluber et al., 2009; Bunnell and Houde, 2010).

2.3. *Statistical analyses*

Because Steinnon Creek had a smaller number of treated trees than the Woodward Creek (Table 2), I combined data from both study areas for analysis and assumed that treated trees in both location were subjected to similar environmental conditions given their proximity to one another (<5 km) and because the study areas were similar in their age class and structure, tree species composition, and topoedaphic features. I performed all analyses using the R statistical environment (v4.3.1, R Core Team, 2023). First, I first used the glm function in the 'lme4' package to quantify tree decay in response to snag creation treatments (Bates et al., 2015). I constructed separate models, each with a binomial distribution and logit link, to evaluate binomial response variables (i.e., tree status, broken bole, peeling bark, cracked bole, shelf fungus present) relative to treatment (categorical) as a fixed effect. To quantify treatment effects on bark cover I constructed a linear model with treatment as a fixed effect and log(bark cover + 1) as the response variable; a similar model was constructed for cavity cover. Given differences in DBH among treatments at the time treatments were implemented (see Results), I also constructed a second model for each of the aforementioned response variables that consisted of an interaction term between treatment and individual tree DBH at the time of treatment (continuous) as a fixed effect, and then used the anova function in the 'car' package (Fox and Weisberg, 2019) to evaluate whether including initial DBH improved model fit. I did not detect any improvement in model fit when DBH at the time of treatment was included (Rivers, unpublished data) so I restrict my presentation to models that contain treatment alone. For testing hypotheses with binomial response variables, I calculated odds ratios using the 'emmeans' package (Lenth, 2023) using the Tukey adjustment to control for Type I error rates; I used the same approach when testing hypotheses for bark cover and cavity cover. Because only 37 treated trees (4.6%) were assigned a decay class score of 5–9, I restricted my analysis to trees with decay class scores of 1–4. To assess the relationship between treatment and decay classes I used the assocstats function in the 'vcd' package which provides inference procedures for categorical data (Meyer et al., 2023). Assumptions were upheld for all statistical models, and I set alpha = 0.05 for all hypothesis tests.

Table 2
The number of trees relocated at Steinnon Creek (treatments implemented in 2001) and Woodward Creek (treatments implemented in 2003) study areas near Coos Bay, Oregon, USA. Mean (± 95% confidence interval [CI]) DBH was measured at the time of treatment implementation.

Treatment abbreviation	Steinnon Creek (n)	Woodward Creek (n)	Mean DBH at treatment (cm)
T1	39	175	56.2 (55.6, 56.8)
T2	39	162	59.5 (58.3, 60.7)
Wound	35	149	61.8 (60.8, 62.8)
Inoc	0	68	67.3 (65.9, 68.7)
T1_Inoc	0	73	56.1 (54.6, 57.7)
T2_Inoc	0	69	58.3 (56.6, 60.0)

3. Results

The field crew searched for 882 treated trees, 151 at Steinnon Creek and 731 at Woodward Creek. Of this total, 809 trees (91.7%) were ultimately relocated, with 113 at Steinnon Creek and 696 at Woodward Creek. Although the mean DBH of all treated trees were similar between the two sites (Steinnon Creek: 59.2 cm [95% CI: 57.7, 60.7], Woodward Creek: 59.4 cm [58.8, 60.1]; $t = -0.35$, $p = 0.728$), mean DBH at the time of treatment varied with trees in the Inoc treatment being > 10 cm DBH larger, on average, than trees in the Top1 treatment (Table 2).

Across treatments, 97.0–98.9% of relocated trees in each treatment remained standing, with no evidence that treatment influenced whether a tree was standing ($\chi^2 = 3.41$, $df = 5$, $p = 0.638$). Because of this, I detected no difference in odds ratios between any of the treatment comparisons that were linked to focal hypotheses (Table 3). Only 19 trees had fallen in the 18–20 years since treatments were implemented; 5 trees had evidence of having been cut intentionally and therefore were removed from all analyses. Trees that fell naturally comprised all treatments: 6 trees in T1, 6 trees in T2, 2 trees in Wound, 2 trees in Inoc, 2 trees in T1_Inoc, and 1 tree in T2_Inoc. The type of snagfall observed in treated trees included butt rot (8 trees), tip up (4 trees), and bole snap (2 trees); there was no clear pattern between snagfall type and treatment. Fall orientation of trees ranged from 81–280°. The proportion of tree mortality varied widely across treatments, with the two intensive chainsaw topping treatments having the highest mortality (T1: 99.1%, T1_Inoc: 91.8%) followed by the less intensive chainsaw topping treatments (T2: 50%, T2_Inoc: 46.4%), Inoc (5.9%) and Wound (3.8%).

In contrast to the treatments not being linked to whether a tree was standing, there was strong divergence among treatments in the extent to which treated trees were observed with a broken bole ($\chi^2 = 119.88$, $df = 5$, $p < 0.001$), had peeling bark ($\chi^2 = 297.96$, $df = 5$, $p < 0.001$), harbored cracks along the bole ($\chi^2 = 239.71$, $df = 5$, $p < 0.001$), or had evidence of fungi along the bole ($\chi^2 = 52.73$, $df = 5$, $p < 0.001$; Fig. 2.). In general, the more intensive chainsaw topping treatment (T1) showed greater evidence of decay than other treatments, followed by the less intensive chainsaw topping treatment (T2; Table 3). Similarly, when the more intensive chainsaw topping treatment was combined with fungal inoculation (T1_Inoc) it typically led to more decay than when the less intensive chainsaw topping treatment was combined with fungal inoculation (T2_Inoc), although the extent of the differences depended on

Table 3
Odd-ratios of binomial responses variables for the hypotheses being evaluated in this study as described in Table 1.

Prediction	Response variable	Odds ratio (± 95% CI)	*z*	*p*
T1 > T2	Standing	0.64 (0.08, 5.23)	-0.61	0.991
	Broken	2.87 (1.44, 5.73)	4.34	< 0.001
	Bark peeling	5.74 (3.09, 10.66)	8.03	< 0.001
	Cracks	4.00 (2.08, 7.00)	6.30	< 0.001
	Fungus	1.97 (1.08, 3.57)	3.22	0.016
T1_Inoc > T1	Standing	0.85 (0.08, 9.56)	-0.19	1.000
	Broken	1.10 (0.49, 2.46)	0.35	1.000
	Bark peeling	0.94 (0.42, 2.13)	-0.22	1.000
	Cracks	1.00 (0.55, 3.00)	0.72	0.980
	Fungus	0.95 (0.44, 2.08)	-0.18	1.000
T2_Inoc > T2	Standing	1.05 (0.04, 28.79)	0.04	1.000
	Broken	1.50 (0.55, 4.07)	1.15	0.862
	Bark peeling	0.71 (0.27, 1.88)	-0.99	0.922
	Cracks	1.00 (0.32, 2.00)	-0.58	0.992
	Fungus	0.90 (0.36, 2.20)	-0.35	0.999
T1_Inoc > T2_Inoc	Standing	0.52 (0.02, 17.70)	-0.53	0.995
	Broken	2.11 (0.72, 6.23)	1.97	0.359
	Bark peeling	7.54 (2.50, 22.78)	5.21	< 0.001
	Cracks	6.00 (1.94, 16.00)	4.62	< 0.001
	Fungus	2.09 (0.74, 5.87)	2.04	0.321
T1_Inoc > Inoc	Standing	1.08 (0.06, 19.38)	0.07	1.000
	Broken	39.33 (2.05, 752.60)	3.55	0.005
	Bark peeling	63.36 (7.29, 550.91)	5.47	< 0.001
	Cracks	72,483,754 (0.00, Inf)	0.04	1.000
	Fungus	11.81 (2.35, 59.45)	4.35	< 0.001
T2_Inoc > Inoc	Standing	2.06 (0.06, 69.95)	0.59	0.992
	Broken	18.61 (0.94, 369.26)	2.79	0.059
	Bark peeling	8.40 (0.92, 77.04)	2.74	0.068
	Cracks	12,843,717 (0.00, Inf)	0.03	1.000
	Fungus	5.65 (1.07, 29.81)	2.97	0.036

which response variable was evaluated (Table 3). I also found that there was no evidence of enhanced decay when fungal inoculation was added to either of the chainsaw topping treatments (Table 3), and that the inoculation treatment (Inoc) had little effect on any measure of decay (Table 3). Finally, both the Wound and Inoc treatments had limited evidence of decay except for the presence of fungi on Wound trees (Fig. 2).

Treated trees had clear treatment differences in bark cover among treatments ($F = 12.72$, $p < 0.001$) and most trees retained a large amount of bark cover (Fig. 2E). Trees in T1 had less bark cover (i.e., more decay) than T2 ($\beta = -0.14$ [95% CI: -0.23, -0.05], $t = -4.43$, $p < 0.001$) with a similar difference between T1_Inoc and T2_Inoc ($\beta = -0.16$ [95% CI: -0.32, -0.01], $t = -3.03$, $p = 0.030$). There was no evidence that chainsaw topping + fungal inoculation led to reduced bark cover relative to chainsaw topping alone for both levels of chainsaw topping (T1_Inoc vs. T1: $\beta = -0.03$ [95% CI: -0.15, 0.10], $t = -0.62$, $p = 0.989$; T2_Inoc vs. T2: $\beta = -0.00$ [95% CI: -0.13, 0.13], $t = -0.10$, $p = 1.000$). Finally, bark cover was reduced when intensive chainsaw topping was combined with fungal inoculation (T1_Inoc) relative to inoculation (Inoc) alone ($\beta = -0.24$ [95% CI: -0.39, -0.08], $t = -4.36$, $p < 0.001$), whereas no differences in bark cover were detected when the less intensive chainsaw topping was combined with fungal inoculation (T2_Inoc) relative to inoculation (Inoc) alone ($\beta = -0.07$ [95% CI: -0.23, 0.09], $t = -1.32$, $p = 0.774$).

Treated trees had very low levels of cavity cover, with clear treatment differences ($F = 119.67$, $p < 0.001$; Fig. 2F). Cavity cover was greater for the more intensive, than the less intensive, topping treatment ($\beta = 0.92$ [95% CI: 0.70, 1.13], $t = 12.22$, $p < 0.001$), irrespective of fungal inoculation treatment ($\beta = 1.09$ [95% CI: 0.72, 1.45], $t = 8.52$, $p < 0.001$). There were no differences detected in cavity cover for either level of chainsaw topping when combined with fungal inoculation (T1_Inoc vs. T1: $\beta = 0.19$ [95% CI: -0.10, 0.48], $t = 1.84$, $p = 0.439$; T2_Inoc vs. T2: $\beta = 0.02$ [95% CI: -0.28, 0.32], $t = 0.18$, $p = 1.000$). In contrast, there was greater cavity cover for both topping treatments when combined with fungal inoculation relative to inoculation alone (T1_Inoc vs. Inoc: $\beta = 1.72$ [95% CI: 1.36, 2.09], $t = 13.47$, $p < 0.001$; T2_Inoc vs. Inoc: $\beta = 0.64$ [95% CI: 0.27, 1.01], $t = 4.92$, $p < 0.001$). Finally, there was strong evidence that tree decay class was not independent of treatment ($\chi^2 = 579.30$, $df = 15$, $p < 0.001$; Fig. 3). Tree decay was more advanced in the more intensive chainsaw topping treatment (Fig. 3A) and the more intensive chainsaw topping + fungal inoculation treatment (Fig. 3E). In contrast, snag decay classes were comparatively low in the mechanical wounding (Fig. 3C) and inoculation treatments (Fig. 3D).

4. Discussion

The key finding emerging from this study was a strong divergence among snag creation treatments in the extent of tree decay 18–20 y post-treatment. In particular, I found that (1) mechanical wounding and fungal inoculation had limited efficacy for creating snags and promoting structural diversity 2 decades after treatment, (2) combining fungal inoculation with chainsaw topping led to little increase in the extent of decay relative to chainsaw topping alone, and (3) chainsaw topping - especially when leaving < 2 branch whorls – led to the greatest amount of decay. In regards to the first finding, the association between woodpeckers and fungi has long been known (Conner et al., 1976; Jackson and Jackson, 2004) and fungal inoculations have been used promote nesting substrates for primary cavity nesters and other saproxylic species for many decades (Conner et al., 1983; Brandeis et al., 2002; Bednarz et al., 2013; Wainhouse and Boddy, 2022). However, there has been mixed results for using fungal inoculation to create snags during the first 10 y post-treatment (Filip et al., 2004, 2011; Bednarz et al., 2013), particularly for trees that experienced fungal inoculation alone. I also found that fungal inoculation treatments led to limited decay characteristics, and that combining fungal inoculation with chainsaw topping did little to enhance decay relative to chainsaw topping alone. Why fungal inoculation did not promote decay is unclear, but a leading explanation is that for this treatment to be effective it requires a longer evaluation period than has occurred in prior studies (Filip et al., 2011; Bednarz et al., 2013). Fungal growth and subsequent decay stemming from experimental inoculation can occur at a slow pace in conifers (Brandeis et al., 2002; Filip et al., 2011; Bednarz et al., 2013) and lead to tree decline and mortality across a sizable timescale (Franklin et al., 1987). This suggests the time that elapsed between inoculation treatment and re-measurement in this study may also have been insufficient for extensive decay processes to occur. Indeed, the fungal inoculant used in this study (*P. pini*) has been described as living as long as 100 y and it may take 40–50 y before fungal fruit-bodies are found in abundance on treated trees (Lõhmus, 2016). Thus, additional monitoring over future decades may be needed to fully assess the effectiveness of fungal inoculation treatments. Nevertheless, results from this study add to a growing body of literature that has found that fungal inoculation, particularly when practiced alone, is insufficient to induce decay over the shorter timeframes often desired by managers (Brandeis et al., 2002; Filip et al., 2011; Bednarz et al., 2013). Thus, if the goal of treatment is to produce rapid tree decline and/or mortality, there are more suitable methods available, such as chainsaw topping (Bull and Partridge, 1986; Brandeis et al., 2002; Bednarz et al., 2013)

Similar to fungal inoculation, mechanical damage to the base of trees led to limited enhancement of decay with almost no evidence of use by woodpeckers as measured by cavity cover; however, ca. 25% of mechanically damaged trees harbored shelf fungi (Figs. 1D, 2D) and thus were experiencing internal decay. Unlike the more common method of base girdling (Lewis, 1998; Kane et al., 2019), mechanical basal damage in this study was limited to one-third of the circumference, resulting in tree decline but not mortality. Aside from the presence of shelf fungi, mechanically damaged trees had little other evidence of external decay,

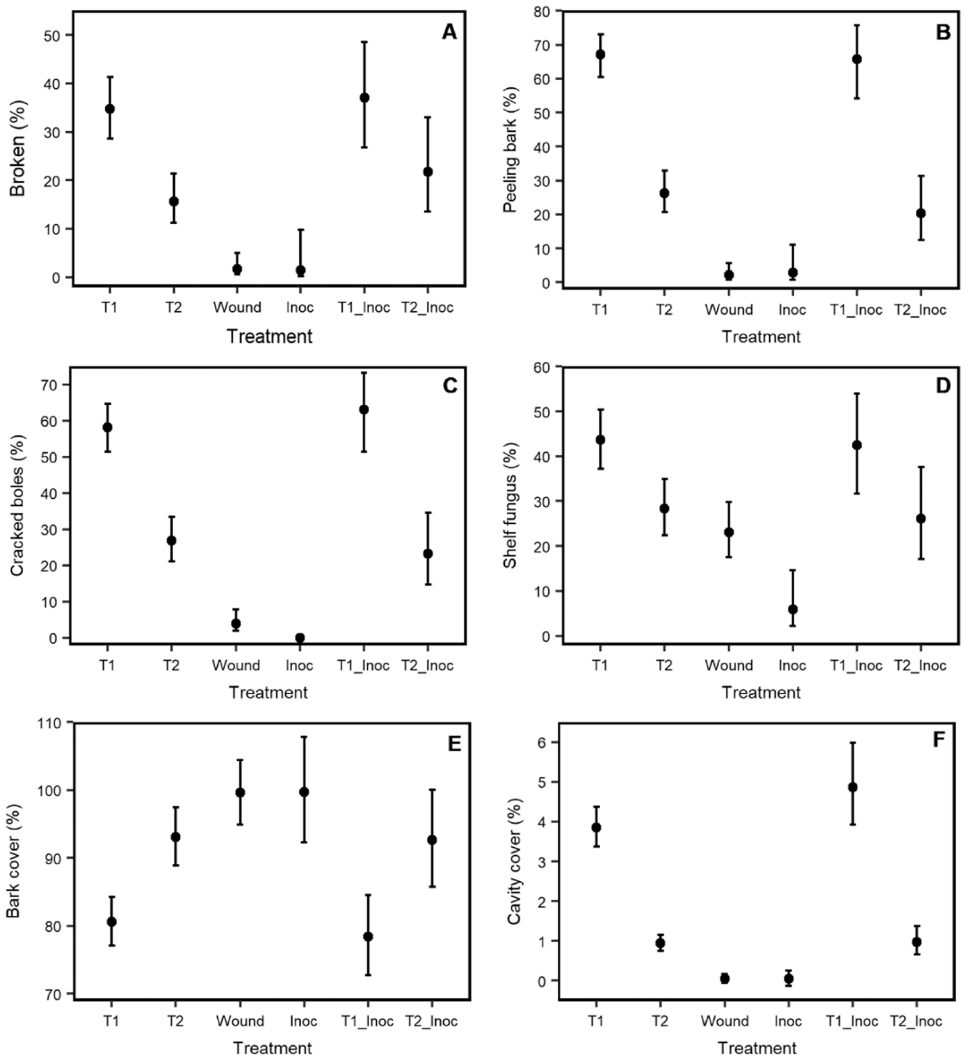

Fig. 2. Extent of decay characteristics among treatments as expressed by the mean percentage (± 95% CI) of trees with (A) a broken top, (B) peeling bark, (C) cracks along the bole, (D) shelf fungi, (E) bark cover, and (F) cavity cover. Treatment abbreviations follow those in Table 1.

and trees in this treatment exhibited almost no cavity cover, suggesting they were likely poor foraging and nesting substrates for woodpeckers (Bednarz et al., 2013; Barry et al., 2017). Mechanically damaged trees in this study also experienced an average increase in diameter of 10.6 cm (95% CI: 9.6, 11.5) by the time of re-measurement (Rivers, unpublished data), indicating continued growth for at least part of the post-treatment period. Thus, although the mechanical damage treatment did reduce tree health, the limited evidence of decay and use by woodpeckers suggests this treatment was ineffective at enhancing habitat elements for wildlife in the two decades following treatment. One would expect trees that experienced mechanical damage will eventually be used by saproxylic species as trees continue to decline, so re-assessing such trees at a future date would be worthwhile. It would also be valuable to compare the extent of decay in mechanically damaged trees with those that received the fungal inoculation treatment alone in future decades, as the financial costs of mechanical damage treatments is lower because it does not require fungal pathogen husbandry nor tree climbing for implementation (Bull and Partridge, 1986; Lewis, 1998; Bednarz et al., 2013).

Of the treatments evaluated in this study, chainsaw topping was the most effective at enhancing tree decay and leading to use by woodpeckers within two decades of treatment, albeit the latter was at rather low levels. Of the three treatments that included topping, the treatment in which topping left < 2 live branch whorls (T1) was more effective than topping that left 2 or more live branch whorls (T2). Chainsaw topping is used widely to create snags (Bull and Partridge, 1986; Chambers et al., 1997; Lewis, 1998; Brandeis et al., 2002) but depending on the location and extent of topping, some trees can remain alive after treatment (Bull and Partridge, 1986; Brandeis et al., 2002; Huff and Bailey, 2009). Although non-fatally topped trees often enhance structural complexity within the canopy, such outcomes may be misaligned with management goals of snag creation treatments, particularly those aimed at boosting snag abundance in managed forest landscapes where standing dead wood has become rare (Kroll et al., 2012). Both topping treatments yielded decay during the period of observation (T1 to a greater extent than T2), thus both may enhance structural diversity over longer timeframes. That I found no evidence of a boost in decay when fungal inoculation treatments were combined with chainsaw topping is likely due to sufficient fungal growth occurring because of natural colonization processes (Bednarz et al., 2013). Thus, adding fungal inoculation to trees that are topped with chainsaws does not appear to be worth the additional expense and time.

Findings from this study were largely consistent with prior work evaluating created snag treatments. For example, the high rate of trees that remained standing after topping was similar to investigations that evaluated topping over long (> 15 y) timescales (Barry et al., 2017; Halpern et al., 2022). This study also found that tree mortality was greater with fewer live branches remaining on topped trees, as noted by Huff and Bailey (2009) when examining topped trees 16–18 y

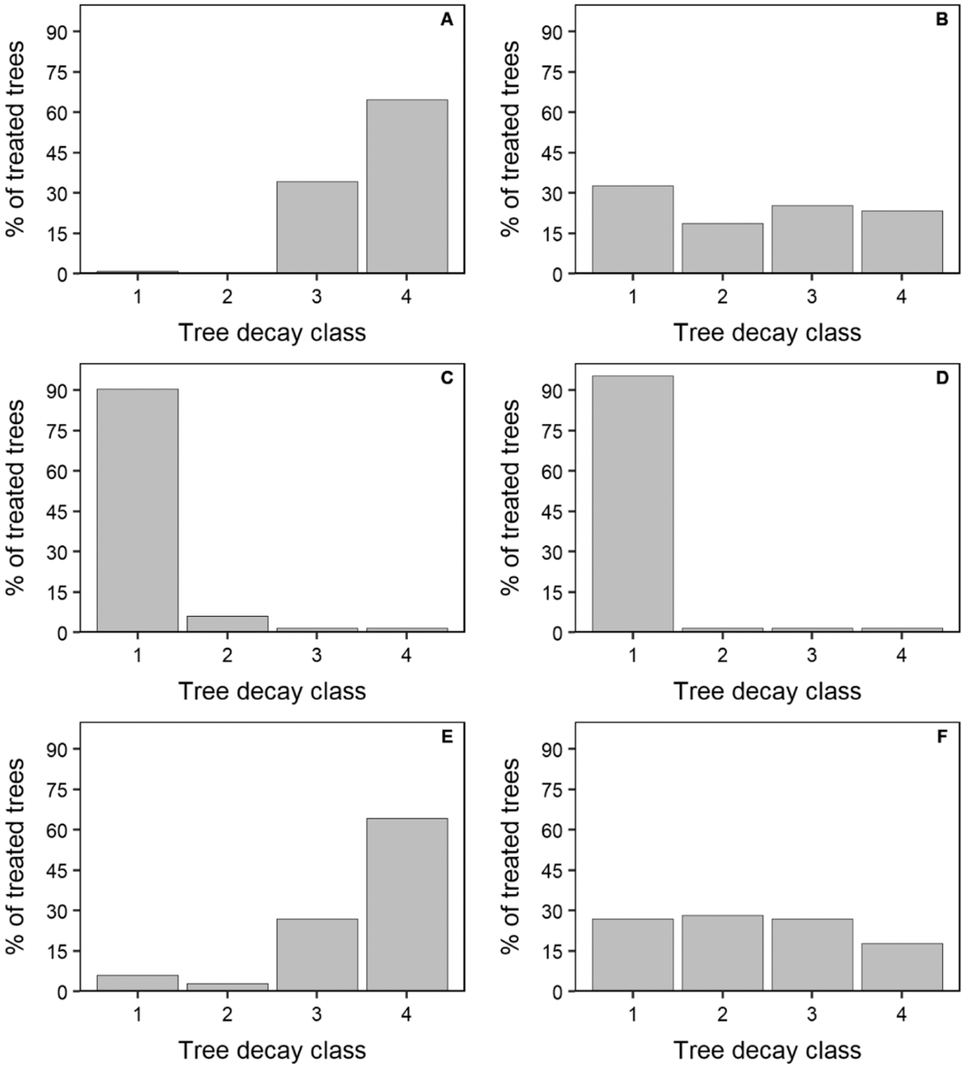

Fig. 3. Distribution of tree decay classes following treatments (A) T1, (B) T2, (C) Wound, (D) Inoc, (E) T1_Inoc, and (F) T2_Inoc; treatments follow the nomenclature in Table 1. Tree decay classes were based on Maser et al. (1979) as follows: 1 = live, 2 = declining, 3 = dead, 4 = dead with loose bark. A total of 37 treated trees (<5%) had more advanced decay (i.e., decay classes 5-9) but were excluded from analysis due to low representation.

post-treatment. Likewise, the limited efficacy of fungal inoculation parallels results from prior work undertaken over intermediate timescales (7–14 y post-treatment; Filip et al., 2011; Bednarz et al., 2013). This study builds upon these findings and shows that fungal inoculations are unlikely to cause tree death alone, and it extends prior research by showing that combining fungal inoculation with topping does not increase the likelihood of creating a snag. As noted above, there are few studies examining mechanical wounding at the base as a snag creation method but other forms of tree wounding – some of which also involve the use of fungal inoculation – are gaining popularity for creating habitat elements for some taxa (Terry et al., 2021; Wainhouse and Boddy, 2022; Griffiths et al., 2023). Nevertheless, the finding that treated trees grew after extensive mechanical damage is germane to studies that use tree wounding to create cavities, and it emphasizes the need to re-evaluate wounding treatments over time to determine if such treatments are negated by tree healing processes (Griffiths et al., 2023).

This study found that contemporary treatments used to create snags and wildlife trees to enhance structural diversity varied markedly in their efficacy two decades after treatment. Despite these differences, all the treatments had some type of decay 18–20 y post-treatment and one would expect more decay in the future (Lõhmus, 2016). These findings make it clear that when managers are selecting a treatment(s) to implement, they should consider the timespan for which it is desirable to have tree decay. If the goal is to promote more rapid decay (e.g., within 5 years), chainsaw topping appears most effective. However, if the goal is to promote slower decay over longer timeframes (e.g., decades), mechanical damage is more appropriate. Moreover, implementing multiple treatments concurrently that differ in the timeframe they take for decay to develop may extend the total period during which treated trees in an area are available to deadwood-dependent wildlife. In addition to providing a longer period of decay, implementing different snag creation treatments may also circumvent reentry into stands to implement treatments at multiple points in time, streamlining workflows and reducing implementation costs. Additionally, when targeting trees for wildlife, managers should take into consideration live trees that may already have characteristics that benefit to deadwood-dependent species, such as those with broken tops, large dead branches, and conks indicative of existing heart rot. Such an approach may be particularly useful in conjunction with snag creation to ensure a continuum of decay across long timescales.

Although the findings from this investigation can help guide managers in their selection of the treatment(s) that will be most effective at fulfilling management goals, several lines of additional research are needed for an improved understanding of snag creation methods. First, there are few long-term studies of that re-measure created snags > 15 y after treatment (Barry et al., 2017; Kane et al., 2019; Halpern et al., 2022; this study). Nevertheless, studies that meet – or exceed – this timeframe are critical for understanding decay processes that occur over many decades (Lõhmus, 2016). Second, contemporary estimates regarding the financial cost of implementing snag creation treatments are lacking, which are needed for quantifying the tradeoffs between the ecological benefits and financial costs that result from intentional snag creation. Finally, there is a need to synthesize results from snag creation treatments across studies given the wide variation in creation methods, forest types, tree species, and environmental conditions, all of which have potential to influence the efficacy of snag creation. New studies investigating these topics will provide a better understanding of snag creation over long timescales and help maximize the efforts of managers implementing such treatments.

CRediT authorship contribution statement

James W. Rivers: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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