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Changes in bark properties and hydrology following prescribed fire in *Pinus taeda* and *Quercus montana*

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Abstract

In the eastern United States, the use of prescribed fire as a silvicultural technique to manage for desirable upland tree species is increasing in popularity. Bark physical properties such as thickness, density, and porosity have known associations with fire tolerance among species. These physical properties simultaneously influence rainfall interception and canopy storage and thus are of interest across a range of disciplines. Furthermore, while these characteristics are innate to a species, it is unknown whether repeated exposure to fire facilitates physical change in bark structure and whether these changes are consistent among species. To answer these questions, bark samples were collected from mature pine (*Pinus taeda* L.) and oak (*Quercus montana* Willd.) trees from sites across the Bankhead National Forest in Alabama, USA under three different burn regimes: 3-year cycle, 9-year cycle, and no fire. Samples were analysed in the laboratory for bulk density, porosity, water storage capacity, and hygroscopicity (the amount of atmospheric water vapour absorbed by bark during non-rainfall conditions). Drying rates of saturated samples under simulated wetting conditions were also assessed. Oak bark had higher bulk density, lower porosity, and dried slower than pine bark. Interestingly, bark from both species had lower bulk density, higher porosity, greater water storage capacity, and dried faster in stands that were burned every 3 years compared to other fire regimes ($p < 0.001$). In summary, this study demonstrates that prescribed fire regimes in an eastern US forest alter bark structure and thus influence individual tree control on hydrological processes. The increase in bark water storage capacity, coupled with faster bark evaporation times may lead to less water inputs to the forest floor and drier overall conditions. Further investigation of this fire-bark-water feedback loop is necessary to understand the extent of these mechanisms controlling landscape-scale conditions.

KEYWORDS
bark density, bark hygroscopicity, bark porosity, Chestnut oak, loblolly pine, prescribed fire

1 | INTRODUCTION

Tree surfaces play a critical role in forest hydrology. Both bark and leaves act as temporary storage reservoirs in forest canopies during rainfall events, wherein the bark usually has a greater water holding capacity than the foliar surface (Llorens & Gallart, 2000). While water clings to external surfaces of leaves, water can be retained on both external bark surfaces and absorbed into internal bark tissues. Thus, knowledge of both external bark morphology and internal structure is needed to quantify how much rainwater will be diverted into storage and how much will make it to the forest floor as throughfall or stemflow. Characteristics such as bark thickness, density, and porosity all influence bark water storage capacity and vary among tree species (Ilek et al., 2021). These bark differences among species are manifested in different rates of rainfall partitioning among species and across forest stands (André et al., 2008; Barbier et al., 2009; Van Stan and Levia, 2010; Siegert et al., 2020). These same bark physical traits are also important adaptations for fire tolerance.

In eastern North American forests, historical fire regimes created positive feedback loops whereby open-forest landscapes were maintained with species tolerant to fire (e.g., *Quercus* and *Pinus* spp.) that in turn, supported more flammable conditions (Nowacki and Abrams, 2008; Hanberry et al., 2020). In the fire-vegetation feedback loop, thick bark is one adaptation enabling species to survive fire (Barlow et al., 2003; Hammond et al., 2015; Hengst & Dawson, 2011; Pellegrini et al., 2017), along with other characteristics such as fuel loads that perpetuate future fire, resprouting ability. Thicker bark will simultaneously have a greater storage capacity to absorb rainwater (Levia & Herwitz, 2005), thus increasing the quantity of rainfall that is intercepted and decreasing the quantity of rainfall that makes it to the forest floor as throughfall or stemflow. Less water inputs to the forest floor would mean a drier fuel bed and higher flammability, leading to more conducive conditions for further fire and for the success of fire-adapted species on those sites.

There is both empirical and model-derived evidence of the role of bark thickness in fire-vegetation feedback loops. Thicker bark reduces cambium temperatures and increases the time it takes to kill the cambium, ultimately decreasing the risk of mortality (Hengst & Dawson, 1994; Pausas, 2015). Additionally, consideration of the thickness of bark relative to stem size is a strong predictor of protection from fire damage and mortality (Lawes et al., 2013). However, bark thickness is just one of several physical properties of bark structure that may be important to both fire survival and forest water budgets. For example, Uhl and Kauffman (1990) found that thin exfoliating bark becomes hotter than fissured barks with greater surface areas during a fire event because the external bark features like bark roughness often affect external bark temperatures.

Other physical and structural properties of bark include density, porosity, and hygroscopicity. While bark thickness can easily be measured non-destructively in situ, these latter characteristics require destructive sampling (Ilek et al., 2017; Ilek & Kucza, 2014). As such, our understanding of these properties across species and how these properties have evolved relative to fire disturbance are less well known. A tradeoff between bark density and porosity has been observed among species with similarly thick bark in southeastern US forests. Hickories (*Carya ovata*, *C. glabra*) had the densest bark followed by upland oaks (*Q. alba*, *Q. stellata*, *Q. pagoda*, and *Q. shumardii*) with intermediate density, and pines (*P. taeda*) with the least dense bark (Ilek et al., 2021). The opposite trend for porosity was observed, with pines have the greatest porosity, oaks with intermediate porosity, and hickories with the least porosity (Ilek et al., 2021). A significant variation in bark density among tree species has also been reported by Miles and Smith (2009) and Bauer et al. (2010). Meyer et al. (1981) showed that density differed between outer and inner bark, (i.e., the density of inner bark is usually less than outer bark), which was also reflected in less moisture content in outer bark (Ugulino et al., 2020). Ilek et al. (2017) found strong positive relationships between and bulk density of eight European tree species and strong inverse relationships between bark hygroscopicity and total porosity. This study also demonstrated that the proportion of maximum bark water storage that was attributed to hygroscopicity varied from less than 10% of maximum bark water storage in *P. sylvestris* to more than 30% in *Betula pendula* (Ilek et al., 2017), thus suggesting interspecific differences in bark morphology that control bark hydrological properties.

Depending on whether bark pore space is occupied by air or water will also influence how individuals respond to fire. The transfer of heat from fire outside of the bark to the cambium can be modelled using heat transfer coefficients where heat is more readily transferred at the outer side of the bark than at the inner side (Bauer et al., 2010). Bark porosity has been shown to inversely affect the rate of heat transfer, where more porous bark has lower thermal conductivity. However, these models assume a steady state of porosity and do not currently take into account whether the pore space is occupied by air or water. Finally, bark moisture content may influence fire tolerance and survivability. On the one hand, higher bark moisture content has been shown to conduct heat more efficiently than open pore space, leading to faster cambium death (Vines, 1968; Wesolowski et al., 2014). Alternatively, higher bark moisture content may prevent the upward spread of fire into tree crowns. However, bark moisture content changes in response to atmospheric moisture conditions and is not a static characteristic like density, porosity, or hygroscopicity. Thus, the objectives of this study were to quantify differences in (1) bark physical properties (density and porosity), (2) bark hydrologic properties (water storage capacity, hygroscopicity, evaporation rates) across co-occurring species of pine and oak and determine how these properties change within a given species depending on the fire regime.

2 | MATERIALS AND METHODS

2.1 | Study site and sample collection

Bark samples were collected from loblolly pine (*Pinus taeda* L.) and chestnut oak (*Quercus montana* Willd.) (Figure 1) at Bankhead National Forest in northern Alabama in Fall 2019 from stands with three different fire regimes: (1) no fire, (2) an infrequent 9-year fire return interval and (3) a frequent 3-year fire return interval. All stands were thinned to 17 m^2 ha^{-1} residual basal area in 2006 and dormant season fire treatments commenced thereafter (Schweitzer et al., 2016). The stand with infrequent 9-year fire return interval was burned twice prior to bark sample collection (20 December 2006 and 10 February 2016). The stand with frequent 3-year fire return interval was burned five times prior to bark sample collection (30 January 2007, 25 February 2010, 16 March 2013 and 21 March 2019).

Eight trees per species across the three fire regimes were selected for sampling for a total of 48 trees (Table 1). All trees were dominant canopy trees with an average diameter at breast height

FIGURE 1 Contrasting bark characteristics of loblolly pine (left) and chestnut oak (right).

TABLE 1 Summary of average and standard error of tree size (DBH, diameter at breast height) bark thickness, and relative bark thickness calculated as the ratio between bark thickness and the stem radius (Hoffmann et al., 2012) of trees sampled across different fire regimes

	DBH (cm)		Bark thickness (mm)		Relative bark thickness (%)	
Fire frequency	LP	CO	LP	CO	LP	CO
3-Year Return Interval (Frequent)	36.3 ± 1.4	38.3 ± 2.0	15.0 ± 1.1	12.6 ± 0.8	8.2 ± 0.5	6.6 ± 0.4
9-Year Return Interval (Infrequent)	36.9 ± 1.0	35.4 ± 1.2	17.0 ± 1.2	11.7 ± 0.5	9.3 ± 0.8	6.6 ± 0.2
No Fire	32.3 ± 0.9	35.6 ± 1.4	11.8 ± 0.7	11.3 ± 0.6	7.3 ± 0.4	6.4 ± 0.4

Abbreviations: LP, Loblolly pine; CO, Chestnut oak.

(DBH) of 35.8 cm, ranging from 30.0 to 48.7 cm. Bark sections approximately 15 cm by 30 cm, including inner and outer bark, were extracted from each tree at breast height down to the vascular cambium using hammers and chisels, stored in paper bags, and returned to the laboratory for analysis. Most trees in stands where prescribed fire had occurred had char marks at breast height where samples were obtained. When char marks were not present, samples were taken at random cardinal direction on the stem.

2.2 | Laboratory experiments

In the laboratory, bark sections were separated into six equal sized pieces using a band saw and analysed. Bulk density was measured in three bark replicates from each tree as the ratio of dry mass to volume of bark. To measure volume, bark samples were first submerged in water for 5 days until samples were fully saturated then volume was measured via the water displacement method in a graduate cylinder (Ilek et al., 2017). Samples were then dried to a constant mass at 105°C and weighed for final dry mass. Specific density was determined by the pycnometer method in 99.8% ethyl alcohol (Ilek et al., 2017). A subset of bark samples from each individual tree were ground and aggregated into one bark sample for each tree. After homogenizing and drying the ground bark at 105°C, specific density was determined on a 2 g sample from each tree. Total porosity of bark was calculated following the equation:

$$TP = \frac{SD - BD}{SD}, \quad (1)$$

where TP (cm^3 cm^{-3}) is total porosity, SD is specific density (g cm^{-3}) and BD is bulk density (g cm^{-3}).

Actual hygroscopicity was determined following the methods of Ilek et al. (2021). Actual hygroscopicity was measured by placing oven-dried bark samples in desiccators, with water filling the bottom reservoir instead of desiccant, to establish an environment with 100% relative humidity. Samples were sealed with silicone caulk on all surfaces except exterior bark, dried at 35°C, and weighed prior to placement in the desiccator then weighed at 2-day intervals until mass stabilization. Actual hygroscopicity was then calculated as

$$S_{HA} = \frac{M_{final} - M_0}{V} \times 10, \quad (2)$$

where S_{HA} is the actual hygroscopicity a particular bark sample (mm of water in bark sample standardized to a thickness of 1 cm), M_{final} is the mass of the sample after mass stabilization was achieved indicating maximum absorption capacity (g), M_0 is the initial mass of the dry sample (g), V is the volume of the sample as determined from BD measurements (cm^3), and 10 is a factor of conversion into mm of H_2O in bark sample with a thickness of 1 cm.

Water storage capacity of bark was determined after actual hygroscopicity measurements by immersing bark samples in water for 7 days until fully saturated. The bark samples were then weighed, dried at 105°C for 24 hours, and weighed again. Water storage capacity was calculated following Equation 2.

Evaporation rates of moisture loss from saturated samples were performed in environmental chambers under controlled conditions of 12 h at 20°C and 12 h of 10°C to simulate daytime and nighttime temperatures during the growing season. Bark samples were again

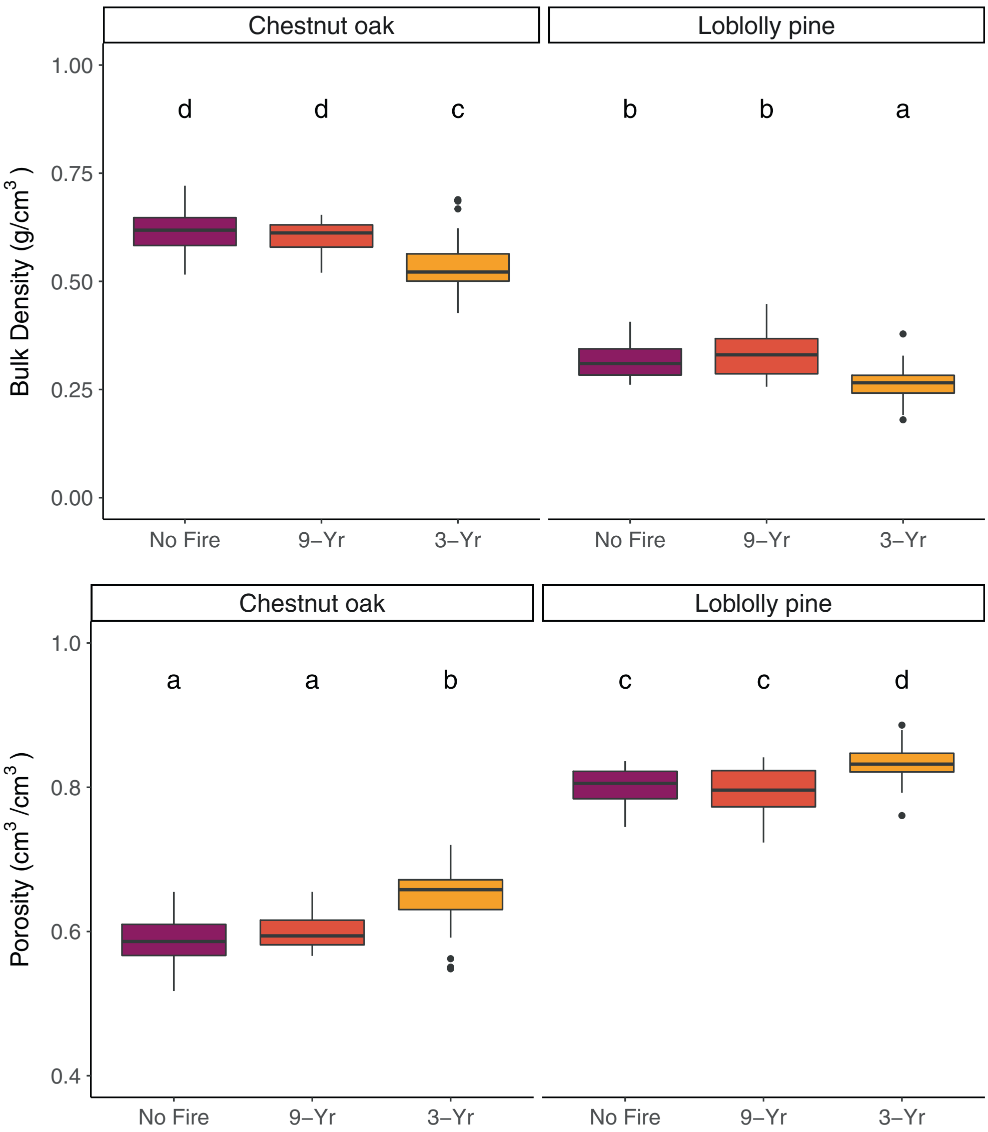

FIGURE 2 Bulk density (top panels) and porosity (bottom panels) differences between chestnut oak and loblolly pine across three different fire return intervals. Letters indicate significant differences in bulk density among samples ($p < 0.05$).

submerged in water until fully saturated, weighed for initial saturated mass, then placed in environmental chambers. Samples were weighed at 2, 6, 24, 48, 72, 120, and 144 h to capture the exponential decay shape of the drying curve.

2.3 | Statistical analysis

Differences in bark physical properties including bulk density, porosity, bark water storage capacity, and bark hygroscopicity among species and burn regimes were determined through linear mixed models in R version 4.1.0. Bark physical properties were considered fixed effects and individual trees were considered a random effect. When differences were detected, least-square means post-hoc analysis was performed using lsmeans in the emmeans package in R (Lenth et al., 2019).

3 | RESULTS

In terms of physical bark properties, chestnut oak bark was 1.9-times more denser than loblolly pine bark (Figure 2). Frequent fire with a 3-year return interval resulted in bark that was 12% less dense in chestnut oak and 19% less dense in loblolly pine compared to bark density from stands with infrequent fire return intervals (9-year) or no fire (Figure 2). For total porosity, loblolly pine bark was 1.3-times more porous than chestnut oak bark across all fire regimes (Figure 2). Frequent fire (3-year return interval) resulted in bark that was 9% more porous in chestnut oak and 5% more porous in loblolly pine.

Bark water storage capacity was similar in chestnut oak (4.19 mm H_2O per cm bark thickness) and loblolly pine (4.25 mm H_2O per cm bark thickness) ($p = 0.086$). However, differences in bark water storage capacity were evident among fire regimes ($p < 0.001$) (Figure 3). Bark water storage capacity was lowest in bark with an infrequent

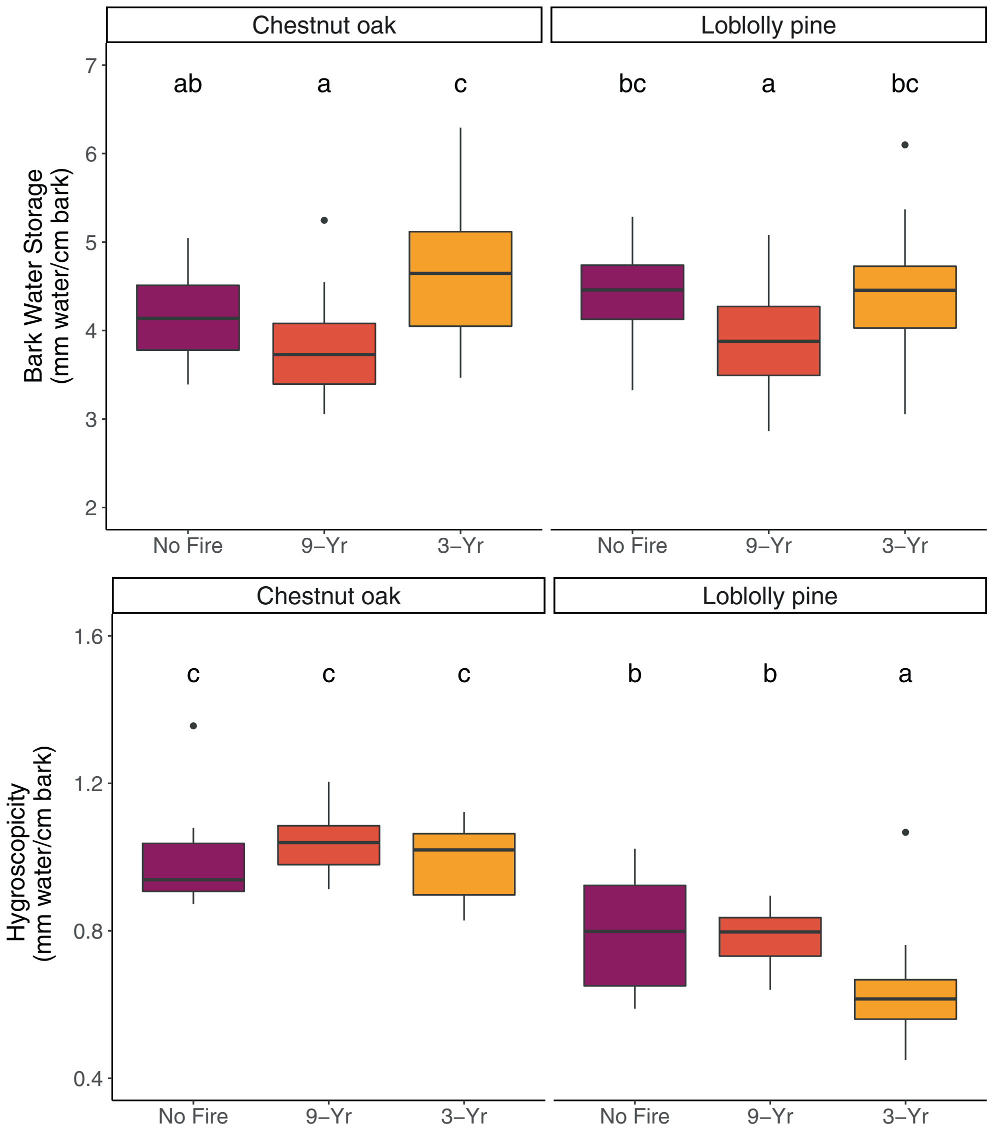

FIGURE 3 Bark water storage capacity (top panels) and hygroscopicity (bottom panels) differences between chestnut oak and loblolly pine across three different fire return intervals. Letters indicate significant differences in bulk density among samples ($p < 0.05$).

9-year fire return interval (3.83 mm H_2O per cm bark thickness), intermediate in bark with no fire (4.29 mm H_2O per cm bark thickness) and highest in bark with a frequent 3-year fire return interval (4.54 mm H_2O per cm bark thickness).

At the species level, bark hygroscopicity was 40% greater in chestnut oak compared to loblolly pine (1.01 vs. 0.74 mm H_2O per cm bark thickness, $p < 0.001$) averaged across all fire regimes (Figure 3). In loblolly pine bark, hygroscopicity was 25% lower in trees under frequent 3-year fire return intervals compared to other fire regimes ($p = 0.009$), but no differences were detected in chestnut oak hygroscopicity due to fire frequency ($p = 0.656$).

Under controlled environmental conditions, loblolly pine had faster evaporation of water from bark compared to chestnut oaks with 23% mass loss versus 15% mass loss from evaporation over 1 week (Figure 4). For Chestnut oak, bark from trees experiencing infrequent fire has the slowest rates of evaporation and bark from trees with frequent fire had the fastest rates of evaporation, with differences becoming more pronounced with time. In Loblolly pine, bark from frequent fire regimes had faster evaporation than bark from other fire regimes.

4 | DISCUSSION

Physical and hydrological properties between two co-occurring species and three different prescribed fire regimes were investigated in this study. Regardless of fire regime, Chestnut oak bark has greater bulk density and hygroscopicity, lower porosity, and slower rates of bark water evaporation compared to loblolly pine. However, there was no obvious species difference in bark water storage. In frequent fire regimes, we found that bark density was lower and total porosity was higher in both chestnut oak and loblolly pine. We also found that frequent fire decreased hygroscopicity, but only in loblolly pine. Thus, an increase in porosity would suggest there is more internal bark pore space to store water and consequently, water flowing down stems would be absorbed into bark rather than continuing to the base of the

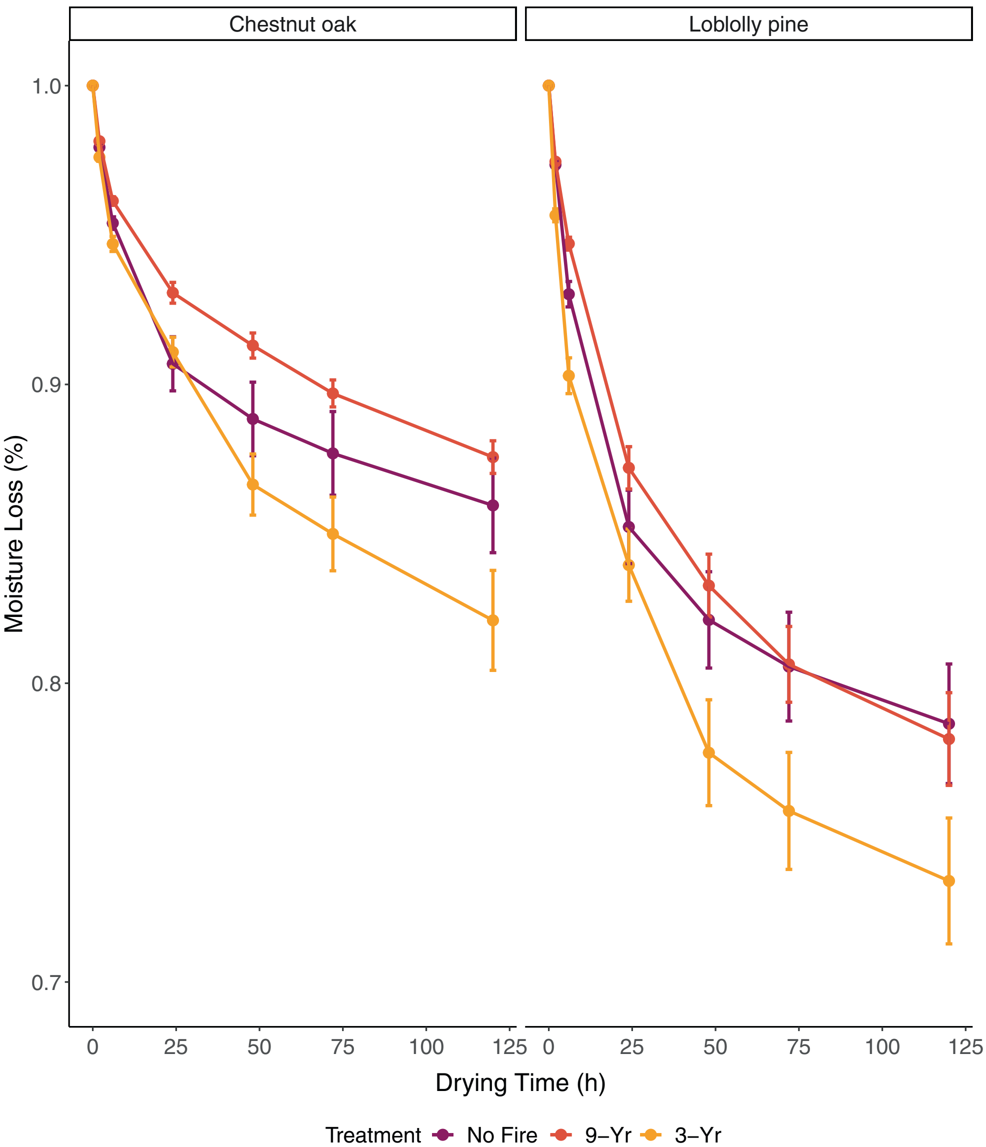

FIGURE 4 Bark water evaporation in environmental chambers.

stem as stemflow (Cayuela et al., 2018). Alternatively, decreased hygroscopicity suggests that water is not as readily absorbed from atmospheric moisture and may be due to hydrophobicity as a result of bark charring in the same mechanism that occurs in soils after fire (Hueso-González et al., 2018; Robichaud, 2000). The faster bark drying times across both species in the most frequent fire return intervals aligns with these other changes observed in bark structure. If water stored in bark evaporates faster in stands with more frequent fire, then there would be more open pore space ready to absorb more moisture during rainfall and/or via atmospheric moisture. The coupling of greater water storage capacity and faster evaporation of stored water within the bark under more frequent fire regimes could ultimately lead to less water inputs to the forest floor and drier overall fuel beds. Although these hydrologic influences are localized to individual tree boles, extrapolating the influence of individual trees across an entire stand could theoretically impact stand-level conditions as well. This type of positive feedback cycle could be an additional way that fire-tolerant species facilitate environments conducive to fire at the individual tree or species level (Babl et al., 2019; Alexander et al., 2021; McDaniel et al., 2021).Thus, an increase in porosity would suggest there is more interior bark pore space to store water and consequently, water flowing down stems would be absorbed into bark rather than continuing to the base of the stem as stemflow.

One potential mechanism for this response in bark structure could be that following exposure to fire and damage recovery, the inner living tissue of bark recovers from fire damage through several mechanisms. For example, Romero and Bolker (2008) observed that species with fast wound closure rates had less compartmentalization of xylem decay, which lead to wide xylem vessels and a decrease in wood density. This was in comparison to species with slower wound closure rates that were better at compartmentalizing xylem decay, leading to less change in wood density, but still a reduction, nonetheless. As such, changes in structure (i.e., density) of the inner, living bark may be manifested to the outer bark as the tree ages (Van Stan et al., 2021). The structural responses observed in Romero and Bolker (2008) occurred within two-years after initial injury. At that timescale, there would be sufficient recovery and adaptation time for trees in our study to response and manifest differences in both the frequent and infrequent burn regimes. Additionally, Romero et al. (2009) demonstrated that *Quercus* species growing across habitats with differing levels of fire intensity and frequency displayed similar response in their wound response. They found that only some *Quercus* species, specifically those in the white and live oak subclades, exhibited the same tradeoffs in wound closure rates, xylem decay, and wood density. While the fire intensity of stands utilized in this study were low, there was likely nominal damage to bark in areas experiencing char, and therefore could have similar structural responses observed in the above studies during recovery processes.

This study is novel in that bark samples were collected from trees that experienced repeated exposure to low-intensity fire in a controlled experimental design (Schweitzer et al., 2016). Our consideration of species that are part of the low-intensity but high-frequency fire regime of the southeastern US provides insights that are not yet addressed in the literature. Passive pyrophytes, species that are merely tolerant of fire but do not require fire, are common in the region. These species do not need to develop excessively thick bark to withstand high-intensity fires such as those found in the high-intensity fire regimes. Instead, the thickness of the bark must only be sufficient to withstand moderate fires. For example, the depth of necrosis in wood tissues was linearly correlated with the flux of heat through bark for commonly occurring hardwoods in eastern US forests (Bova & Dickinson, 2005). This trend was consistent across both thinner-bark species (e.g., *Acer rubrum*) and thicker-bark species (e.g., *Quercus montana*), with thicker-bark species mediating more heat and therefore avoiding deeper necrosis compared to thinner-bark species (Bova & Dickinson, 2005). These results, in conjunction with results from our study, show preliminary evidence of how moderate bark characteristics enable fire insensitivity and tolerance in eastern tree species. Furthermore, our investigation at the stand level, not at some experimental plot level, contributes to the value in discerning response at a broader landscape level.

In our study, the differences observed in bark characteristics after repeated fire involve increased porosity and lower bulk density. In chestnut oak, there was no difference in bark thickness among fire regimes ($p = 0.340$). This suggests that the outer layers of bark were not removed via combustion and that differences in bark structural characteristics cannot be attributed to the loss of external bark layers.. In loblolly pine, there were differences in bark thickness among fire regimes, with bark from no fire being 30% thinner (than having an average thickness of 11.8 mm) than bark from infrequent fire (17.0 mm) ($p = 0.007$), but bark from the frequent fire regime had intermediate bark thickness of 15.0 that was not significantly different from the other two fire regimes. This also suggests that the most frequent fire regime was not consuming the outer bark. It is possible that internal structural differences were arising in response to fire. In the fire-prone Brazilian Cerrado, Loram-Lourenço et al. (2020) demonstrated that bark thickness was inversely related to bark density. In other studies, using the modified wick-fire technique to simulate fire by heating bark to desired temperatures (Hengst & Dawson, 1994; Lawes et al., 2011), it was observed that density of bark increased the capacity of bark to conduct heat and kill the inner cambium. As such, findings of our study that show lower bulk density and greater porosity in more frequent fire is consistent with the literature. Furthermore, it has also been shown that bark with greater hygroscopicity may retain water that can reduce the internal bark temperature and buffer the cambium from extreme heat by consuming energy via latent heat of evaporation instead of conducting energy inwards (Brando et al., 2012). While the specific biological mechanisms that trigger these changes in bark structure following repeated exposure to fire are still not well understood, there is consistency in results across species and ecosystems of these processes occurring.

5 | CONCLUSIONS

In conclusion, this study demonstrates differences in bark thickness, internal structural properties, and hydrologic properties of bark across two species common in upland mixed forests of the eastern US. Despite bark differences between species, relative changes in bark characteristics relative to fire return intervals were similar. Prescribed fire used as a restoration tool in mixed pine-hardwood systems requires the frequent and repetitive implementation of lower intensity fires. This type of fire regime subjects residual trees to stress, albeit a less intense but prolonged one that is repeated as some set interval. How trees respond to this fire regime and repeated stress is paramount to using fire in forest management and is somewhat different than wildfire conditions or conditions found in pine systems (Hood et al., 2018). As such, our study has demonstrated how bark responds to repeated use of prescribed fire.

Our results expand our understanding of the role of bark thickness in protection from fire by exploring internal bark structure that ultimately controls the transfer of heat. The ability of bark to absorb, retain, and evaporate moisture is a key trait that changes with increasing fire frequency and needs further consideration from perspectives of both fire ecology and forest hydrology.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Scholars Junction at https://scholarsjunction.msstate.edu/cfr-publications/23.

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