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Diurnal Pine Bark Structure Dynamics Affect Properties Relevant to Firebrand Generation

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Abstract: Firebrands are an important agent of wildfire spread and structure fire ignitions at the wildland urban interface. Bark flake morphology has been highlighted as an important yet poorly characterized factor in firebrand generation, transport, deposition, and ignition of unburned material. Using pine species where bark flakes are the documented source of embers, we conducted experiments to investigate how bark structure changes in response to diurnal drying. Over a three-day period in a longleaf pine (*Pinus palustris* Mill.) stand in Florida, we recorded changes in temperature, moisture content, and structure of bark across different facing aspects of mature pine trees to examine the effects of varying solar exposure on bark moisture. We further compared results to bark drying in a pitch pine (*Pinus rigida* Mill.) plantation in New Jersey. Under all conditions, bark peeled and lifted away from the tree trunk over the study periods. Tree bole aspect and the time of day interacted to significantly affect bark peeling. General temperature increases and moisture content decreases were significantly different between east and west aspects in pitch pine, and with time of day and aspect in longleaf pine. These results illustrate that bark moisture and flakiness is highly dynamic on short time scales, driven largely by solar exposure. These diurnal changes likely influence the probability of firebrand production during fire events via controls on moisture (ignition) and peeling (lofting).

Keywords: firebrands; embers; bark; photogrammetry; fuel moisture

1. Introduction

Firebrands, combusting airborne objects lofted during fires [1], are an important consideration for wildland fire managers because they directly influence fire spread and represent the primary cause of structure ignitions during wildfires [2–5]. The challenges posed by firebrands during fire suppression efforts have gained attention in response to the increasing losses from wildfires [6]. Firebrand hazard has been described conceptually as having three components, (1) generation, (2) transport, and (3) ignition of new material [3]; although results of recent studies suggest considering firebrand deposition (location and density of deposited firebrands per m^2s^{-2}) as a fourth component [7,8]. Firebrand structure plays a vital role in each component, influencing combustion characteristics [9], aerodynamics [9–11], and patterning of firebrand deposition [7,8,12], as well as the probability of new materials igniting from firebrands [13]. An understanding of conditions and physical processes that drive firebrands remains limited, however, which restricts the ability to quantitatively evaluate firebrand hazard or its use in fire behavior models [4,12].

The flakey outer-bark of trunks and branches of certain pines and eucalyptus species has long been recognized as a primary source of firebrands [7,14–16] During fires in these forest types, firebrands are generated when bark particles become detached, are ignited, and are transported as combusting material. Detachment occurs through erosion by rapid air movement or combustion at or near the bark connection point, or a combination of these processes, which would be impacted by morphology where its structure influencing particle drag is largely unknown. Field studies have also begun to characterize the morphological patterns of deposited bark firebrands, which have been partially consumed, and demonstrate a need to better understand bark morphology prior to ignition in its original form as parent material of firebrands [7,8,12]. While the structural properties of firebrands have been well characterized, their moisture and temperature dynamics, particularly prior to detaching from the tree stem, are areas of inquiry that deserve further attention. Conceptually, moisture content influences potential firebrand particles by changing aerodynamic properties through changes in mass and physical structure through swelling. Just as with all fuels, moisture content and temperature interact and directly influence the energy available for ignition and combustion of the potential firebrands.

The temperature and moisture content of bark varies in response to changing environmental conditions, though the focus has mainly been on long-term responses [17]. These dynamics are not only driven by seasonal climate and regional weather patterns, but also finer-scale influences, such as diurnal patterns of temperature and humidity within a stand, positioning of neighboring trees, and variability on a given individual tree stem [17]. An important, but poorly characterized, element of bark moisture dynamics is the influence of shading and solar angle on stem irradiance. For instance, bark of an Engleman spruce (*Picea engelmannii* Parry ex Engelm.) in Alberta, Canada was observed to vary 35 °C over the course of a single day and by as much as 15 °C between shaded and unshaded facing sides at a single point in time [18]. Similarly, temperature of lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) bark in British Columbia ranged 17 °C over the course of a day, and varied by as much as 4.5 °C between shaded and unshaded sides at a given time, illustrating the importance of solar exposure [19]. Only a few studies have connected the fine-scale observations of bark temperature or insolation to potential moisture dynamics. Reifsnyder et al. [17] found that bark moisture content varied with solar exposure in red pine (*Pinus resinosa* Ait.) plantations, where moisture ranged from 13% to 26% across cardinal directions, with lower values on east and west exposures. In the same study, measurements of the moisture content of longleaf pine (*Pinus palustris* Mill.) bark suggested a 50-hr equilibrium time-lag. For pitch pine, Stickel [20] reported seasonally low bark moistures in the springtime. For chir pine (*Pinus roxburghii* Sarg.), a thick-barked fire-adapted species, moisture content varied from 40.2% and 80.6% [21], and moisture content in that study likely varied temporally, with temperature linked to patterns of bark peeling and flattening across shaded and unshaded sides of a tree. While these studies all point to the variability of bark as a whole over the long term, they do not examine the potential for much shorter-term and finer-scale dynamics in bark surface flakes.

In this study, we examine the short-term dynamics of bark surface flake moisture and temperature. The objectives of this study are to (1) document diurnal patterns of bark moisture for longleaf pine and pitch pine, two common *Pinus* species of the eastern U.S. that experience frequent fire, (2) report on photogrammetric methods to quantify fine-scale changes in bark relief, and (3) to test the hypothesis that bark morphology of flakey-barked tree species change in response to drying cycles, particularly through the influence of solar radiation. To achieve these objectives, we measure changes in bark morphology on different aspects of mature trees over the course of diurnal wetting and drying cycles, and quantify temporal changes in bark moisture and temperature. We analyze the covariance of these characteristics to examine their importance for driving fine-scale bark morphological change. Our study provides basic information about variation in moisture and temperature for subsequent modeling efforts related to fire brand generation and risk of spot fire ignition.

2. Materials and Methods

2.1. Longleaf Pine Bark Measurements

Longleaf bark was sampled at Tall Timbers Research Station (TTRS), an ~1100 ha property in Leon County, Florida, USA that is managed with frequent fire every 1–3 years. Longleaf pine ecosystems are among the most fire-prone forest in the world, with control and escape issues being a large concern [22]. Climate data are provided in Figure S1.

Three mature longleaf pine trees with diameters greater than 40 cm were selected to measure bark characteristics over three consecutive days in May 2019. Custom frames were placed at 1.4 m height on three aspects of each tree (north, southeast, and southwest) to delineate areas of approximately 20 × 25 cm for collecting bark morphology and temperature data (Figure 1A). In addition, outer-most bark flakes were destructively harvested directly below each sampling frame to measure moisture content. These observations and sampling began following a week of dry weather and were conducted three times a day (0800, 1100, and 1400 EDT).

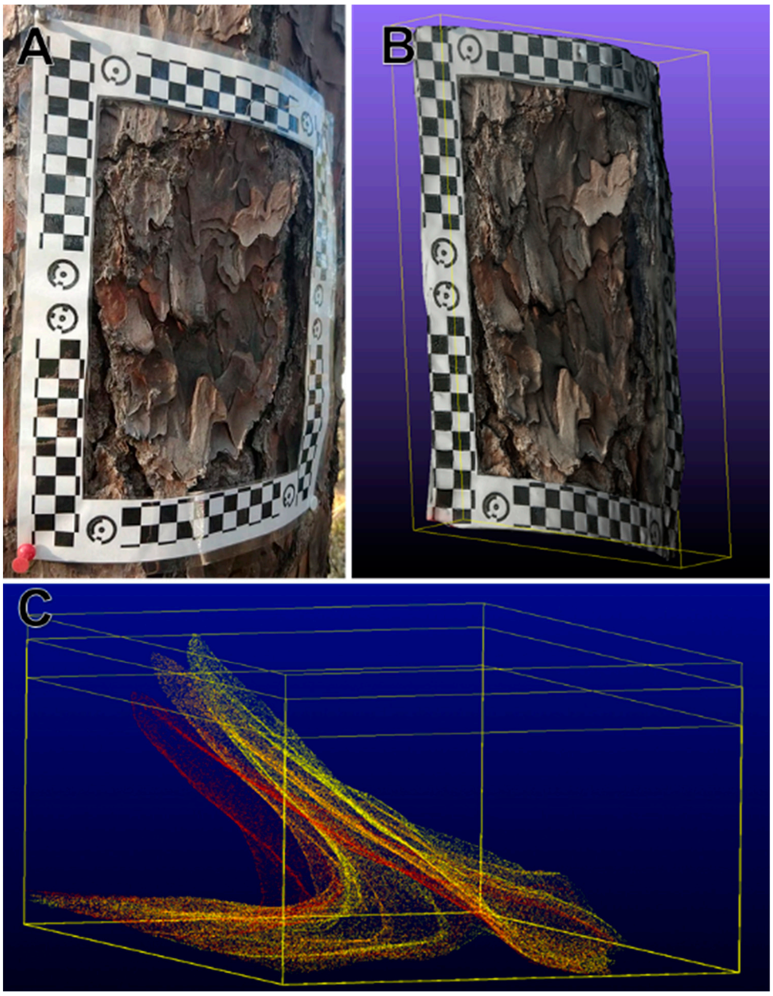

Figure 1. (**A**) Many individual images of longleaf bark inside a custom scaling frame were processed in photogrammetry software to produce a (**B**) three-dimensional model that can be sampled and analyzed. (**C**) A single bark flake cropped from a model tracked through a single day, red at 0800, orange at 1100, and yellow at 1400. The bounding box heights represent the bark flake apex distances from the bark surface that peels away through each time period.

2.2. Pitch Pine Bark Measurements

Pitch pine is a fire-dependent species long recognized for the important role of embers in wildfire spread [19]. The New Jersey Pinelands National Reserve is a 400,000-ha fire-adapted region on the Atlantic Coastal Plain of North America, dominated by pitch pine forests. Frequent, fast-moving, wildfires have been typical of this landscape [23,24], with bark flakes being noted as the critical source of firebrands [7,8,14].

Data were collected from three trees located in a 54-year-old pitch pine plantation at the Silas Little Experimental Forest, previously described by Kuser and Knezick [25] on 9 August 2018. The trees were similar in size (DBH = 24–27 cm) and had been excluded from fire for at least 30 years. Climate data are provided in Figure S2. Frames like those described above were installed at breast height on east- and west-facing aspects of each tree's trunk. Over the course of a single day, measurements of bark morphology, temperature, and moisture content were made hourly from 1100 to 1700 EDT following collection and processing procedures.

2.3. Collection and Processing Procedures

For photogrammetric analysis, mobile devices with 1080p video resolution cameras were used to collect approximately 1800 images from many angles required to adequately create an accurate model. Images were imported into 3DF Zephyr photogrammetry suite (3DFlow, Verona, Italy) to create three-dimensional bark surface models. Surface models were imported into CloudCompare (V 2.10) and re-scaled from default units to metric units, using 1 cm squares on the observation area delineation frame, which was included in all images and subsequently cropped to just bark within the frame (Figure 1B). Point clouds were layered on top of each other and oriented so that apex of a bark flake from each point cloud would move in a vertical plane perpendicular to the tree bole as they peeled or flattened (Figure 1C). The change in distance at a bark flake apex from each model was recorded between time periods. A FLIROne Pro (FLIR Systems Inc., USA) infrared camera was used to measure bark set at an emissivity of 1.0 surface temperatures at a distance of 0.25 m from each target without shading targeted bark at an accuracy of 0.1 °C. Bark flakes were collected from one of the nine sample locations below each frame, and were immediately weighed for wet weights, dried for 48 h at 70 °C, and reweighed for dry weights used to calculate bark moisture content. The thickness of the collected bark flakes was representative of bark flakes used in the photogrammetric analysis ranging from 0.25 to 2 mm in longleaf pine and 0.5 to 3 mm in pitch pine.

$$MC = \left(\frac{WW - DW}{DW}\right) \cdot 100, \quad (1)$$

where MC is moisture content (%), WW is wet weight, and DW is dry weight. Reference ambient weather information was collected at a long-term weather station at both study sites (Figures S1 and S2).

2.4. Data Analysis

Mean differences in bark peeling, moisture, and temperature were tested using a MANOVA [26], using aspect, time of day, tree, and, in the case of the Florida study, day as factors, followed by post-hoc ANOVA tests following the repeated measures protocol as proposed by O'Brien and Kaiser [27]. Post-hoc ANOVA tests using R (R core team 2020) were used to find specific relationships between bark response.

3. Results

Longleaf pine bark flake peeling (n = 27) was related to aspect ($p = 8.85 \times 10^{-8}$, time of day ($p = 1.4 \times 10^{-12}$), and individual tree ($p = 5.24 \times 10^{-6}$). Additionally, there was an interaction effect between these factors (p = 0.003). Individual flakes of longleaf pine moved as much as 4 mm away from the surface of the tree daily (Figure 2), despite being more than ten days since precipitation, owing only to moisture addition derived from nighttime relative humidity (RH) ranging from 91% to 95%. Peeling on southwest and north aspects continued throughout the day as RH decreased and duration of solar exposure increased. Conversely, peeling on the southeastern aspects peaked before noon, and began to decline when no longer in direct solar exposure.

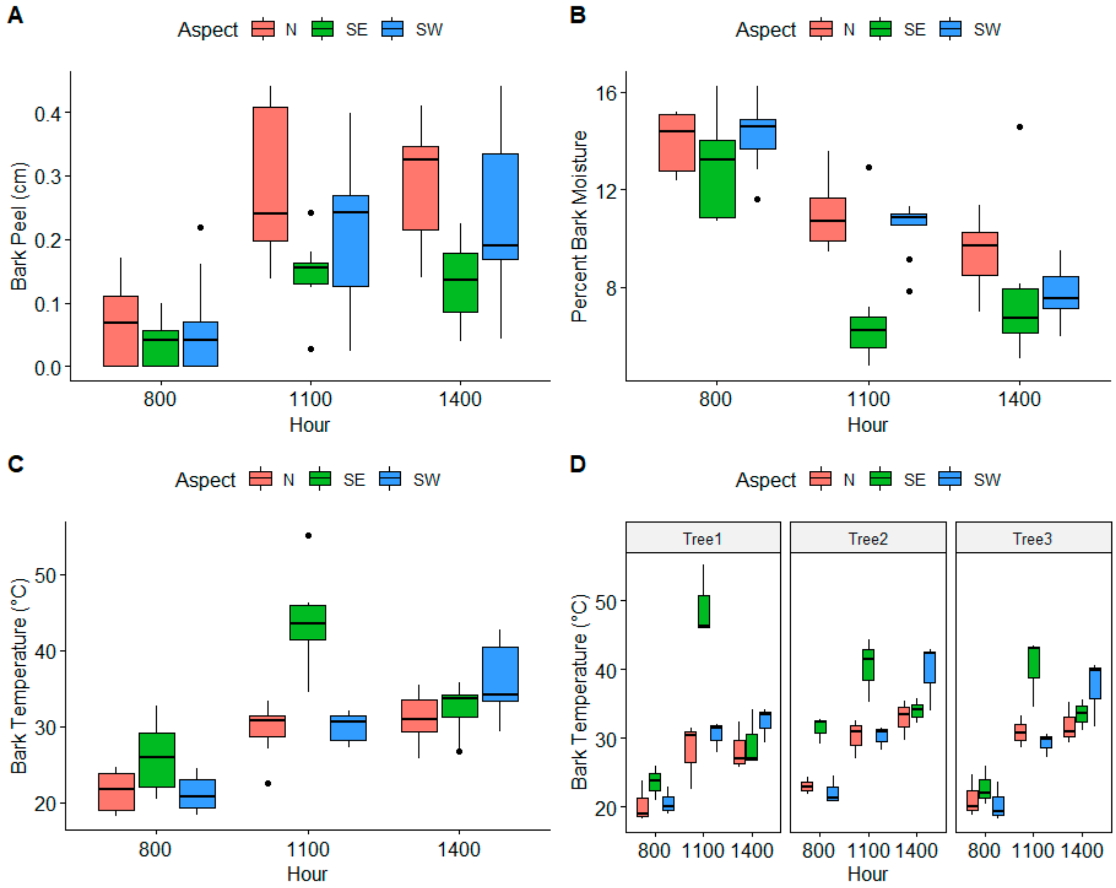

Figure 2. For longleaf pine (**A**) mean bark flake peeling distances (cm) over the duration of the experiment, by hour, separated by aspect (n = 27). Peel distances were adjusted to the lowest point during the experiment. (**B**) Mean percent bark flake moisture over the duration of the experiment by hour, separated by aspect. (**C**) Mean bark surface temperatures (°C) over the duration of the experiment by hour, separated by aspect. (**D**) Three-way interaction of bark surface temperature (°C) by hour with aspect and tree location.

Pitch pine bark also exhibited similar peeling response (n = 21), where hourly trends in cumulative bark peeling were consistently positive and significant ($p = 6.34 \times 10^{-5}$) throughout the day (Figure 3). Cumulative peeling of pitch pine was significantly greater on east aspects than on west aspects ($p = 8.88 \times 10^{-7}$, Figure 3), with cumulative peeling of 6 mm ± 4.8 mm (mean ± 1 standard deviation) and 1 mm ± 0.8 (mean ± 1 standard deviation), respectively.

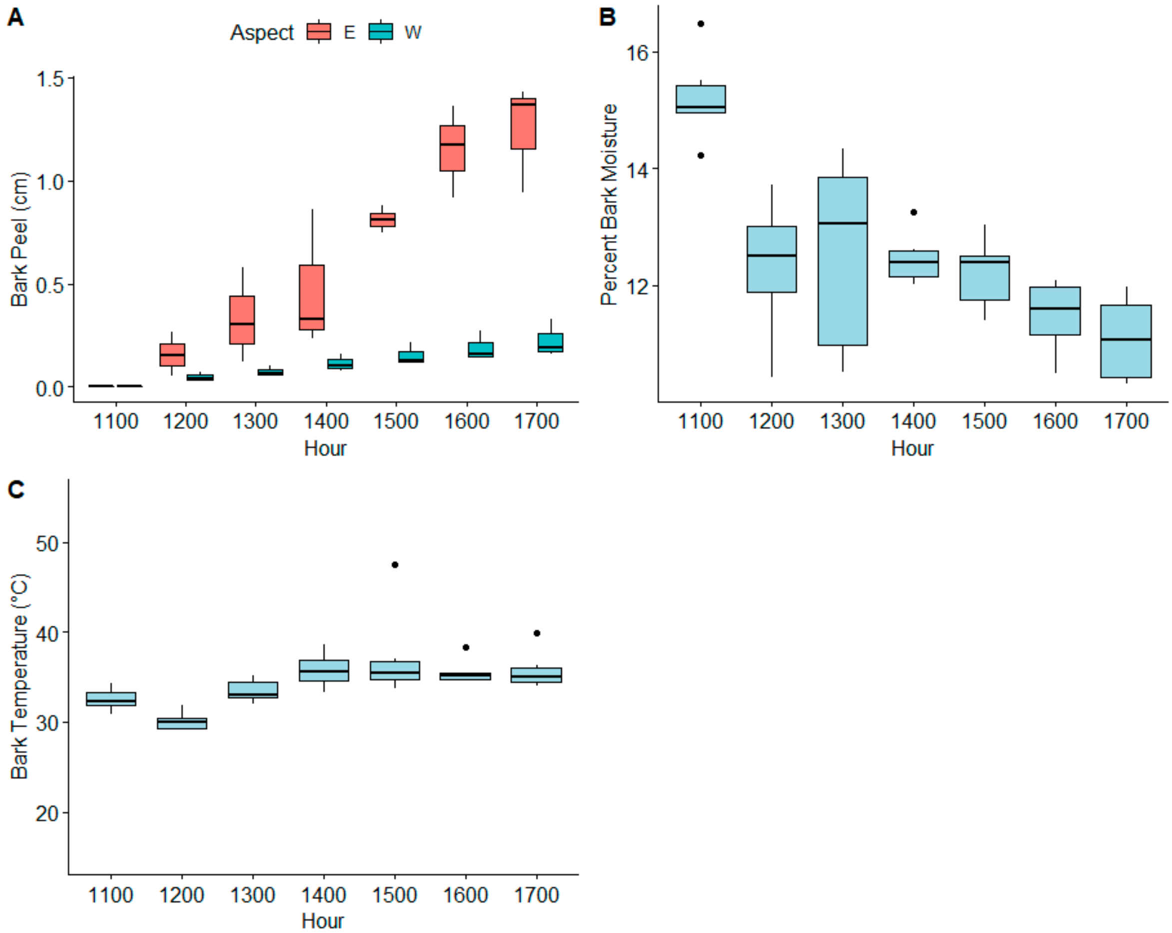

Figure 3. For pitch pine, (**A**) cumulative bark peeling averages (cm) by aspect during the 6-h observation period (n = 21). (**B**) Mean percent bark flake moisture over the duration of the experiment by hour. (**C**) Mean bark surface temperatures (°C) over the duration of the experiment by hour.

Longleaf pine bark moisture content was driven by aspect ($p = 1.06 \times 10^{-7}$), time of day ($p < 2 \times 10^{-16}$), and individual tree ($p = 1.83 \times 10^{-6}$). A three-way interaction of aspect, time of day, and tree was also significant ($p = 0.015$). While moisture at southwest and north aspects had a consistent decreasing trend throughout the day, moisture of the southeast aspect decreased rapidly at peak solar exposure and then began recovering later in the day (Figure 2). Percent bark moisture was not significantly different by aspect during the observation period in pitch pines, but did change through the day ($p = 4.88 \times 10^{-7}$) (Figure 3). Longleaf pine bark surface temperatures were significantly correlated with aspect ($p = 1.00 \times 10^{-6}$), time of day ($p = 1.21 \times 10^{-9}$), and tree ($p = 0.006$). These factors were all influenced by the amount of solar radiation on a tree at a given observation and the interaction was significant ($p = 0.017$). Pitch pine bark surface temperature was not significantly different between aspects, but a small decrease was recorded at noon-time temperatures when the sun angle was at its zenith and western aspects were noted to have had higher peak afternoon temperatures than eastern aspects (Figure 3).

4. Discussion and Conclusions

We found that exposure to solar radiation was a primary driver of patterns of the drying and peeling dynamics of both longleaf pine and pitch pine bark flakes. Diurnal changes in bark surface temperature—particularly elevated temperatures from exposure to solar radiation—were associated with rapid changes in bark morphology (i.e., peeling) and moisture. Understanding the role of solar radiation on bark properties could be useful in assessing fire risk on prescribed fires or wildfires during times when the directional spread of a fire aligns with the tree aspect of greatest solar exposure, and exacerbated with higher ambient temperatures and longer times since rain.

There are relatively few studies that have examined the moisture dynamics of pine bark. Reifsnyder et al. [17] and the Spalt and Reifsnyder [28] review of bark moisture found consistently slow equilibrium moisture responses of red pine, shortleaf pine (*P. echinata* Mill.), and longleaf pine to ambient relative humidity. The lowest bark moisture content recorded in that study was 6% and corresponded to 14% ambient relative humidity [17]. While that study included solar aspect (exposure) for Red Pine, they concluded that bark only responds slowly to changing environmental conditions. Our results, by contrast, showed that exposure to solar radiation produced significantly faster response to diurnal moisture exchange to a subset of outer bark flakes. We measured moisture content as low as 6% in solar-exposed longleaf pine bark under conditions of >60% ambient relative humidity, but the response for pitch pine was more subdued, reflecting canopy forest condition (i.e., denser canopy and fewer sunflecks) of the mature pine plantation. In the presence of sunlight, bark moisture declined by more than 50% in a few hours relative to shaded portions of the tree on the longleaf pines. Tree 1 was on the eastern edge of the stand and southeastern aspect temperatures were greater on that tree, while trees 2 and 3 were in the western edge with southwestern temperatures reaching greater values (Figure 2). Diurnal bark peeling also changed with solar exposure in both species. This diurnal process driving peeling could increase the lofting potential through associated drag forces on peeling bark flakes that would occur during a passing flame front, particularly as the flakes concomitantly heat and lose moisture. Given that the tree boles create dramatically higher velocities of wake eddies on the leeward side of tree bole [29,30], any wind-driven fire that aligned with the sun side of that tree may expect greater firebrand generation and perhaps bark more receptive to sustained combustion while aloft.

Fire managers have long suggested these unique bark dynamics, where they noted that bark morphology of flakey-barked *Pinus* species native to eastern North America change with regard to dryness, gradually curling or peeling out from the trunk or branch's axis of growth. Although this peeling dynamic has not been quantified prior to this work, one plausible mechanism for our observations results from contrasting hydrophobicity of inner and outer bark membranes (e.g., phellogen and old phloem) documented for another common southeastern species, loblolly pine (*Pinus taeda* [31]), which is closely related to pitch and longleaf pines. Mechanistically, contrasting levels of hydrophobicity between inner and outer bark cells would facilitate faster hydration and expansion of cells among inner bark membranes than outer bark cells, thus causing curling or peeling to occur to account for the change in cell size. When all moisture has been driven from the bark, or moisture is returned to the outer cells, the tension relaxes and the bark flattens again. Unpublished lab observations of alternating the wetting and drying of individual bark flakes supports this mechanism. Alternatively, Butler et al. [32] exposed ponderosa pine (*P. ponderosa* Lawson & C. Lawson) bark to high temperatures and noted that some species responded with radial swelling, although these changes did not occur until temperatures reached at least 125 °C.

This study also shows the utility of advanced photogrammetric methods to link basic bark structural changes and moisture characteristics. Future research can leverage the widely available, non-destructive photogrammetry methods presented in this study to further investigate variation in bark morphology under a broader range of species and environmental conditions. For instance, while our work focused lower on the tree trunk, other areas of the trunk within the canopy may experience greater and more direct solar exposure. This may exacerbate bark peeling and enhance ember production during torching or crown fire behavior even at high relative humidity, similar to results reported for surface fuels [33]. Finally, we suggest that future modeling of spotting potential consider that when the leeward side of a tree aligns with solar exposure during a headfire, convective flow and radiative heating along the tree trunk may align with the flakiest, driest, warmest bark, which could easily generate firebrands.

We conclude that the morphology of longleaf pine and pitch pine bark can rapidly respond to diurnal environmental conditions, and these characteristics may be similar in other thick-barked *Pinus* species found throughout the U.S. and globally. These changes include decreased moisture and increased peeling, which collectively could affect fire brand ignition and lofting from the tree. Our results show that pine bark morphology responds rapidly to environmental conditions, and that solar exposure (measured by proxy with aspect and repeated measures sampling) was the most important factor in explaining cumulative bark peeling for longleaf pine and pitch pine. Additionally, photogrammetry methods are simple and non-destructive and present a robust and cost-effective means for future research on fuel moisture and morphology of bark that can be useful for future bark and firebrand studies.

Supplementary Materials: The following are available online at http://www.mdpi.com/2571-6255/3/4/55/s1.

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Conflicts of Interest: The authors declare no conflict of interest.

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