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NOTE

Pine cones facilitate ignition of forest floor duff

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Abstract: The ignition and combustion of forest floor duff are poorly understood yet have been linked to soil heating and overstory tree mortality in many temperate coniferous forests. Research to date has focused on the characteristics of duff that facilitate ignition and spread, including fuel moisture, mineral content, and depth. Field observations suggest that the presence of pine cones on and within the forest floor might facilitate ignition of intermixed forest floor fuels. We investigated the effect of cone fuel additions on the ignition of underlying forest floor from fuels collected in long-unburned longleaf pine (*Pinus palustris* Mill.) forests in northern Florida, USA. Fuels were wetted to threshold gravimetric moisture contents to evaluate the relative effect on ignition. In stark contrast to fuel beds without cones, in which duff ignition only occurred in 17% of samples, those with cones added ignited the underlying duff 94% of the time. Flame heights were 40% taller and flaming duration was 47% longer in fuel beds with cones. Where present, pine cones act as vectors of ignition for forest floor fuels, and their role in fires deserves more attention to enhance our understanding of forest floor combustion.

Résumé : Bien qu'on sache peu de choses au sujet de l'allumage et de la combustion de l'humus dans la couverture morte, le réchauffement du sol et la mortalité des arbres de l'étage dominant ont été mis en cause dans plusieurs forêts de conifères tempérées. À ce jour, la recherche s'est concentrée sur les caractéristiques de l'humus qui facilitent l'allumage et la propagation, incluant la teneur en humidité, la teneur en minéraux et l'épaisseur des combustibles. Les observations sur le terrain indiquent que la présence de cônes de pin dans la couverture morte et en surface pourrait faciliter l'allumage du mélange de combustibles dans la couverture morte. Nous avons étudié l'effet de l'ajout de cônes en tant que combustible sur l'allumage de la couverture morte sous-jacente à l'aide de combustibles prélevés dans les forêts de pin des marais (*Pinus palustris* Mill.) qui n'ont pas brûlé depuis longtemps dans le nord de la Floride, aux États-Unis. Les combustibles ont été humidifiés jusqu'au seuil de saturation selon la teneur en eau gravimétrique pour évaluer l'effet relatif sur l'allumage. Contrastant nettement avec les lits de combustibles exempts de cônes dans lesquels l'allumage de l'humus est survenu dans seulement 17 % des échantillons, l'allumage de l'humus sous-jacent s'est produit 94 % du temps dans ceux qui contenaient des cônes. Les flammes étaient 40 % plus hautes et la durée de l'embrasement 47 % plus longue dans les lits de combustibles contenant des cônes. Où ils sont présents, les cônes de pin agissent comme vecteurs d'allumage des combustibles dans la couverture morte et leur rôle en lien avec les feux mérite d'être davantage étudié afin d'améliorer notre compréhension de la combustion de la couverture morte. [Traduit par la Rédaction]

Introduction

Long-term smoldering combustion of forest floor duff in coniferous forests has a wide range of impacts (Miyanishi 2001; Varner et al. 2005). So-called "duff fires" smolder in fermentation (Oe) and humus (Oa) organic soil horizons, often for hours to days following ignition and have been implicated in mineral soil heating (Busse et al. 2005; Varner et al. 2009), tree stress and mortality (Swezy and Agee 1991; Varner et al. 2007; O'Brien et al. 2010), seed germination (Chrosciewicz 1974), and postfire erosion (Johansen et al. 2001). In spite of the impacts of these fires, the mechanisms of ignition and spread remain poorly understood.

One hypothesized mechanism of ignition and spread of smoldering duff fires is vectored ignition by pine cones or woody fuels (Fonda and Varner 2004; Varner et al. 2009). Surface fires sustained by flammable surface litter can easily ignite pine cones and small woody fuels, and although surface conifer litter burns quickly (ca. <5 min; Fonda et al. 1998; Fonda 2001; Taylor et al. 2004), cones and woody fuels can burn for hours (Fonda and Varner 2004; de Souza Costa and Sandberg 2004; Gabrielson et al. 2012). This long-duration heating has been hypothesized to dry underlying duff, thereby allowing these relatively wet fuels to ignite and smolder beyond assumed moisture content thresholds for duff ignition (Frandsen 1997). Aside from anecdotal observations (e.g., see notes in Fonda and Varner (2004) and Varner et al. (2009)), no empirical research has documented the effect of pine cones on duff ignition.

Our objectives were to quantify the effect of cone fuels on the probability of ignition of duff (Oe and Oa horizons) within intact forest floor fuels. We used southeastern USA longleaf pine (*Pinus palustris* Mill.) forests as a model system, given the prevalence of deep forest floor fuel beds and well-recognized ecological consequences of duff fires in the region's fire-excluded ecosystems (Kush et al. 2004; Varner et al. 2005; O'Brien et al. 2010). We hypothesized that cone fuels would facilitate ignition of duff beyond assumed moisture content thresholds.

Methods

Site description

We collected intact forest floor fuel (litter and duff) samples from a long-unburned (ca. 45 years since last fire) longleaf pine forest at the Ordway-Swisher Biological Station (29°40′N, 81°74′W) in north-

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eastern Florida, USA. The overstory at the collection site (Lower Brantley Lakes) is dominated by mature longleaf pines, with a patchy midstory of oaks (*Quercus laevis* Walt., *Quercus geminata* Small, and *Quercus hemisphaerica* Bart. ex Willd.). The understory is absent, and the forest floor consists of deep (up to 15 cm) litter (Oi) and duff (Oe and Oa) horizons, typical of fire-excluded longleaf pine forests. Soils are deep, excessively well-drained Quartzipsamments (Readle 1990) with minimal slopes (<5%) and an elevation of 36 m above mean sea level. The temperate climate of the region consists of warm humid summers and short winters, a mean annual temperature of 20 °C, and 143 cm of annual precipitation at the study site (Readle 1990).

Forest floor sampling

Eighteen forest floor fuel samples (50 × 30 cm) were extracted from the study site, proximally to 18 randomly selected mature pine trees, for laboratory burning experiments. Nine of these samples were extracted from the forest floor adjacent to tree bases, where a pronounced duff "mound" occurred. The remaining nine samples were extracted from approximately 2 m away from tree bases beyond the duff mound. Intact samples were removed from the forest floor, by using a knife to cut vertically along the perimeter and inserting a flat pan horizontally beneath the lower duff horizon, and immediately transferred to a storage box. Care was taken to ensure that horizons remained intact during transport. Intact cones were collected from the surface of the forest floor from the stand where forest floor samples were extracted. All samples were air-dried and stored until preparation for burning.

Laboratory sample preparation

Each sample was split into two 25 × 30 cm samples for a paired experimental design (burning with or without a longleaf pine cone vector). All samples were oven-dried at 60 °C for 7 days, when no further loss of mass occurred. For each sample, total fuel bed depth, including litter and duff horizons, was measured near the four corners and averaged. Litter (Oi horizon) was subsequently removed and weighed. The remaining duff was weighed, and depth was measured at four points and averaged. Average litter depth was calculated as the difference between duff depth and the total fuel-bed depth for each sample. Water was slowly added to each duff sample until its mass increased by 60% of its dry mass. Sixty percent moisture content is below ignition thresholds for some organic soils (Frandsen 1987; Garlough and Keyes 2011) but above thresholds observed for southern pine duff (Frandsen 1997). In our pilot burning of longleaf pine duff, we observed that only a small fraction of burns (8 of 40) resulted in duff ignition with ≥60% gravimetric moisture content, whereas 12 of 17 ignited at <60% moisture content; therefore, 60% moisture content was used as an estimated threshold for duff ignition in this study. Duff samples were then sealed in polyethylene bags for 7 days to allow moisture to equilibrate within duff strata. For each of the paired duff samples, one was randomly assigned to be burned with a pine cone "vector", the other without a cone. Longleaf pine cones used in experiments were air-dried (ca. 5% moisture content) under lab conditions (20 to 23 °C, 50% to 60% relative humidity) and weighed immediately prior to burning.

Burning experiments

Oven-dried litter was placed back onto their respective duff samples and field bulk density was approximately reconstructed using preremoval litter depth measurements for each forest floor sample. Pine cones (one per sample) were placed onto the surface of litter of samples randomly assigned to cone treatments for burning experiments. Fuel beds were ignited within a few minutes following the removal of litter and cones from the oven to minimize moisture adsorption.

The litter on the 25 × 30 cm forest floor samples were ignited along the short (25 cm) edge using a butane lighter. For each burn, we recorded total flaming duration (s), maximum flame height (cm) above the surface of duff horizons, and whether or not duff ignition and subsequent consumption occurred. Because individual longleaf pine cones can smolder for ca. 1 h (Fonda and Varner 2004) and smoldering combustion can be subtle, we evaluated duff ignition and consumption 2 h following ignition. Both ignition and consumption were determined to have occurred if all of the following were present: visual observations of smoke; glowing combustion (under dark conditions); and measurable duff depth reduction.

Data analysis

For each sample, duff volume (cm^3) was estimated by multiplying average duff depth by the fuel-bed dimensions (depth × area). Duff bulk density was then calculated by dividing duff mass (g) by duff volume (cm^3). Litter mass, duff mass, and duff bulk density were each compared between forest floor positions: tree base (duff mound) and 2 m away from the tree base (no duff mound). The Shapiro–Wilk test and the modified Levene test were used to test for normality and equal variance, respectively. When assumptions were not met, comparisons were made using the Wilcoxon rank-sum test; otherwise, comparisons were made using the Student's *t* test. We tested the independence between duff ignition (ignition vs. no ignition) and forest floor position (tree base vs. 2 m away) using the chi-square test for independence on count data across both binary variables.

To evaluate the hypothesized role of fuel-bed properties on duff ignition, we used logistic regression to model probability of duff ignition (a binary response) with litter mass (g), duff bulk density ($g \cdot cm^{-3}$), and cone presence (binary) as independent predictor variables. Several a priori selected models, including different combinations of predictor variables, were compared using Akaike's information criterion corrected for small sample size (AICc weights) to determine the best-fitting, most parsimonious model (Burnham and Anderson 2002).

Maximum flame height and flaming duration were compared between samples burned with and without pine cones using paired *t* tests. Subsequently, to determine how flaming combustion influenced duff ignition, we used logistic regression to model probability of duff ignition with maximum flame height (cm) and flaming duration (s) as predictor variables. Models were evaluated that included flame height and flaming duration exclusively and together as predictors in the same model. Models were then compared using AICc criterion, as above.

Results

Litter and duff depths of forest floor samples were 8.0 cm (SD 1.4 cm) and 3.4 cm (SD 1.4 cm), respectively. Litter mass of one sample was much higher (240%) than all others and was excluded from all analyses. Litter and duff masses, averaging 71.4 g (SD 28.5 g) and 652.7 g (SD 145.1 g), respectively, did not significantly differ ($p = 0.096$ and $p = 0.476$, respectively) between samples collected near the tree base and at 2 m away from the tree base (beyond the basal duff mound). Likewise, ignition of duff did not statistically differ between positions ($p = 0.251$), and position was therefore excluded from further analyses. Duff bulk density, however, was lower near a tree's base (0.102 $g \cdot cm^{-3}$, SD 0.017 $g \cdot cm^{-3}$) versus beyond the basal duff mound (0.118 $g \cdot cm^{-3}$, SD 0.021 $g \cdot cm^{-3}$) ($p = 0.016$).

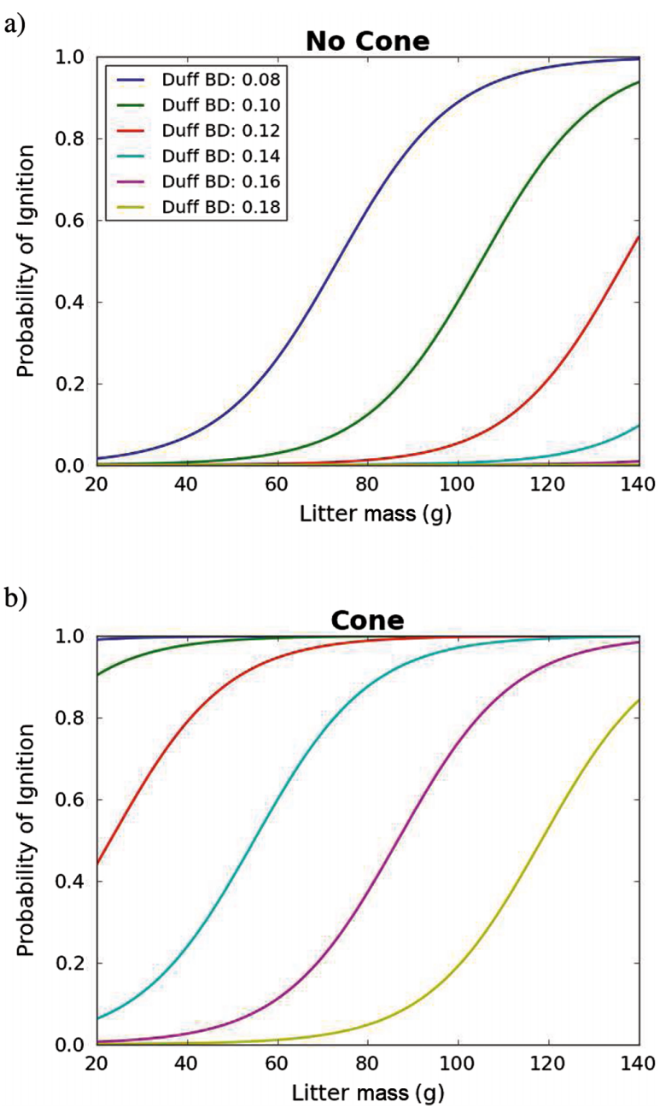
The logistic regression model with litter mass, duff bulk density, and cone presence as predictor variables had the lowest AICc value of all models evaluating forest floor characteristics (Table 1). AICc was 28.2 units lower than the null model, 3.3 units lower than the next best model, and contributed to >75% of the AICc weight of models tested. Parameterization of the model (Fig. 1) indicates an increase in ignition probability with both cone presence and increased litter mass and a decrease in ignition probability at greater duff bulk densities. Standardized coefficients for cone presence, duff bulk density, and litter mass were –8.88, 2.48, and –2.20, respectively, indicating a greater influence of cone

Table 1. Logistic regression models evaluating the effect of pine cones on the probability of duff ignition.

Model	N	Parameters	Log-likelihood	AICc	ΔAICc	AICc weight
$I_{L_{wt}+D_{bd}+C}$	35	4	−6.4317	22.1967	0.0000	0.7506
$I_{L_{wt}+C}$	35	3	−9.3688	25.5118	3.3151	0.1431
$I_{D_{bd}+C}$	35	3	−10.0979	26.9699	4.7732	0.0690
I_C	35	2	−11.9133	28.2016	6.0049	0.0373
I_0	35	1	−24.1314	50.3841	28.1873	<0.0001
$I_{L_{wt}}$	35	2	−23.1950	50.7650	28.5683	<0.0001
$I_{D_{bd}}$	35	2	−23.6016	51.5782	29.38153	<0.0001
$I_{L_{wt}+D_{bd}}$	35	3	−24.1314	55.0370	32.8403	<0.0001

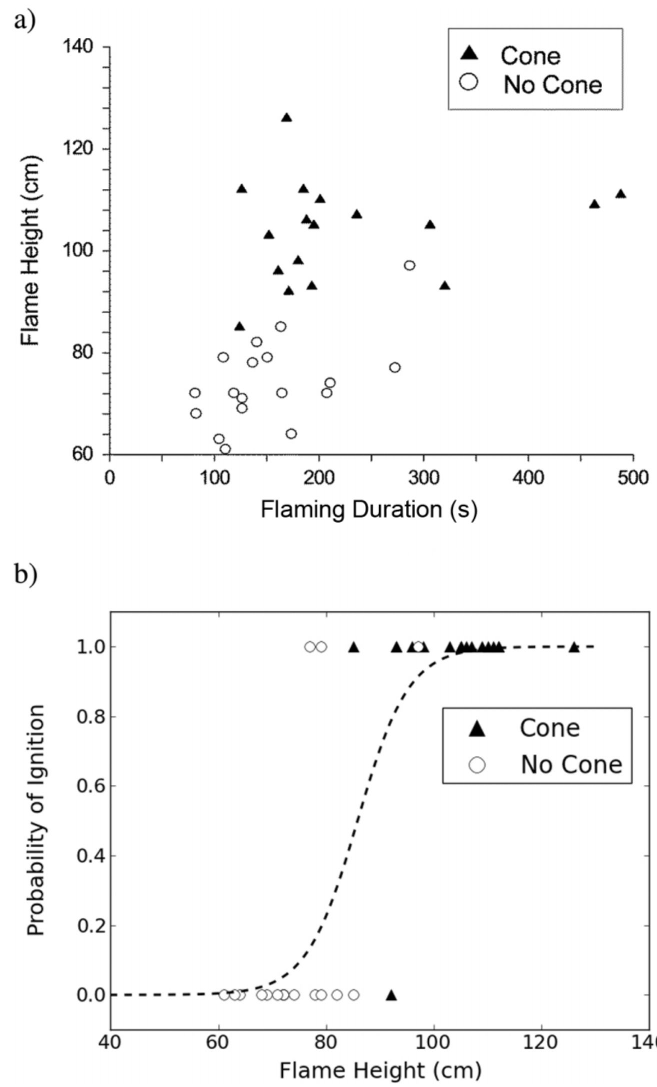
Note: Independent variables: L_{wt}, litter weight; D_{bd}, duff bulk density; C, cone presence; I_0, null model.

Fig. 1. Probability of duff ignition as a function of litter mass, duff bulk density, and longleaf pine cone presence from experimental burns: (*a*) cone not present; (*b*) cone present.



presence than both litter and duff characteristics in the model. Of all models tested, models that included cone presence as a predictor variable constituted >99% of the AICc weight. Sixteen of the 17 burn trials that included a cone vector resulted in duff ignition, whereas only 3 of 18 burn trials without a cone resulted in duff ignition.

Fig. 2. (*a*) Flame height and flaming duration during experimental burning of forest floor samples with and without longleaf pine cones. (*b*) Probability of duff ignition model as a function of flame height.



Both flame height and flame duration were greater ($p < 0.001$ and $p = 0.009$, respectively) during burns that included cones versus burns without cones (Fig. 2). Flame heights averaged 104 cm (SD 10 cm) during burns with cones and 74 cm (SD 9 cm) without cones. Flame duration averaged 227 s (SD 107 s) and 154 s (SD 59 s) during burns with and without cones, respectively. The best logistic regression model predicting duff ignition from flaming behavior (flame height and flame time) was the model including only flame height as a predictor variable (Fig. 2), with a ΔAICc of 31.3 units from that of the null model (Table 2) and accounted for >89% of the AICc weight of models tested.

Discussion

The ignition of longleaf pine forest floor duff in this study was primarily a result of the presence of pine cones. Results are consistent with anecdotal observations in natural fires that vectors of ignition may be critical factors in the ignition and subsequent consumption of these dense organic soil horizons (Fonda and Varner 2004; Varner et al. 2009). Although other factors such as litter mass and duff bulk density may be key components to the ignition and further propagation of duff, "vector" fuels that lie

Table 2. Logistic regression models evaluating the effects of flaming combustion on the probability of duff ignition.

Model	N	Parameters	Log-likelihood	AICc	ΔAICc	AICc weight
$I_{Fl_{ht}}$	35	2	−8.4606	16.9213	0.0000	0.8935
$I_{Fl_{ht}+Fl_d}$	35	3	−7.2027	21.1795	4.2582	0.1063
I_{Fl_d}	35	2	−17.005	34.0093	17.088	0.0002
I_0	35	1	−24.1314	48.2628	31.3416	<0.0001

Note: Independent variables: Fl_{ht}, flame height; Fl_d, flame duration; I_0, null model.

above these layers may be important contributors, especially when moisture levels are near thresholds assumed to inhibit smoldering combustion.

Cones are unique fuels in the forest floor. Unlike woody cylinders, cones can open and close in response to drying (opening) and wetting (closing), entangling needle litter and "ratcheting" into the surface litter horizon. Whether lying on the surface or embedded in surface litter, the field moisture content of longleaf pine cones have been observed to be as low or lower than that of surface litter (Varner et al. 2009), further enhancing their availability as an important fuel. In addition to their arrangement and contribution to fuel mass (Gabrielson et al. 2012), cones, in general, have a high surface area – volume ratio that may enhance community flammability (Fonda and Varner 2004). The substantial variation in cone morphology and mass across *Pinus* suggests that future work addressing variation in cone morphology may highlight relative importance within their respective fire regimes. In spite of the results reported here and anecdotal observations noted above, there is a paucity of research focusing on cone fuels.

Previous work has attributed duff combustibility to properties such as depth, bulk density, mineral content, and moisture content (Frandsen 1987; Garlough and Keyes 2011). Although properties of duff may be important to its ignition and consumption, long combustion times associated with vectors such as cones (Fonda and Varner 2004) or other woody fuels (de Souza Costa and Sandberg 2004; Hyde et al. 2011; Kreye et al. 2011) are capable initiating sustained smoldering of the underlying forest floor (Miyanishi 2001). In this study, the presence of cones overwhelmed the otherwise low probability of duff ignition, whereas combustion of the overlying litter was less important. Fallen leaf litter burns quickly (Fonda 2001; Kane et al. 2008) and produced lower flame heights in this study when cones were not present, reflecting the contribution of cones to energy output during combustion. Although smoldering, solid-phase combustion of cones was not quantified in this study, their contribution to downward heat transfer may also be important for duff ignition. Although cones are often overlooked in fire studies, their contribution to the ignition of duff may, in concert with duff characteristics, contribute to the spatial heterogeneity of duff consumption often observed in the field (Miyanishi 2001). Cones may initiate smoldering combustion, whereas duff properties may control the extent to which these forest floor fuels subsequently burn.

Duff accumulation as a result of fire exclusion presents a challenge for managers attempting to restore fire to long-unburned upland pine ecosystems and to mitigate ecological effects when wildfires occur (Kush et al. 2004; Varner et al. 2005). Smoldering combustion in these dense fuels can often result in significant overstory mortality due to fine root or basal cambium injuries (Ryan and Frandsen 1991; Swezy and Agee 1991; Varner et al. 2007). These management problems are not isolated to southeastern USA pine ecosystems; smoldering combustion is important across several ecosystems where deep organic fuels have accumulated (e.g., Haase and Sackett 1998; Hood 2010; Watts 2013). Our results highlight the importance of compositional heterogeneity of surface fuels that may, in concert with spatial heterogeneity of duff moisture (Hille and Stephens 2005), be an important mechanism for spatial variation observed in duff consumption (Miyanishi 2001). Understanding the diversity of forest floor fuels should be a priority when developing burn prescriptions to meet management objectives and mitigate potential consequences of burning (Varner et al. 2007; Engber et al. 2013). Decision support tools used to aid managers' abilities to predict smoldering combustion will need to take into account the role of vectors contributing to duff ignition. Incorporating vectors into empirical, simulation, and spatially explicit models will enhance our understanding of the complexities of smoldering combustion and better facilitate making forest floor fuels a priority in fire management.

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