Development and Validation of a Moisture-Dependent Forest Floor Fire Behavior Model

Final Report

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I. Abstract

This project addressed smoldering duff fire behavior and fuels characteristics of long-unburned longleaf pine forests in the southeastern USA using a mathematical model, and laboratory and field studies. Model and experimental results showed that significant heating of duff ahead of the smoldering front is limited to a narrow band. Duff properties (moisture, depth, and bulk density) are highly variable across space with autocorrelation typically limited to within 10 m. Drying rates of duff vary widely, even under controlled laboratory conditions, with bulk density partially explaining the variation. Upper duff (fermentation) at tree bases was significantly drier than samples taken 90 cm and further away from trees. This pattern held across wet, dry, and intermediate weather conditions. We provide an evaluation of a sampling device and its utility for managers to assess duff moisture. Our results also showed that in the field, duff near a tree base ignited more easily than duff further from trees. Lastly, in two laboratory studies we 1) showed that pine cones ignite duff that is too moist to be ignited otherwise and 2) that southern litter fuels are diverse in their drying characteristics. These findings improve our understanding of forest floor fuels in long-unburned longleaf pine forests and more broadly for fire-excluded forests elsewhere.

II. Background and Purpose

Forest floor fires have been implicated in extensive overstory tree mortality across disparate fire-prone forested ecosystems. Our understanding of duff smoldering lags, despite its well-recognized importance in tree mortality, emissions, soil heating, and post-burn spatial heterogeneity. Current empirical models that predict consumption of the forest floor generate binary burn no-burn results based on moisture fraction, bulk density, mineral content, and depth. Smoldering duff heats surficial roots and bark, potentially overwhelming the bark and soil properties that protect vascular tissues. The key variable in field experiments has been variation in moisture content across the forest floor horizons. Smoldering temperature and residence time will play an essential role in any biophysically based model to predict such tree mortality. How spatial distributions of moisture content and physical properties of the forest floor interact to generate temperatures and residence times at various locations is an open question. More precisely, no existing model addresses: how moisture and heat move laterally through the forest floor, heating and pre-ignition drying of the forest floor ahead of a smoldering front, and the duration of smoldering.

Post-burn heterogeneity has been identified as a key factor in both limiting soil erosion and promoting species diversity. Again, fuel moisture plays a key role in post-burn heterogeneity. A potential explanation for heterogeneity is that the forest floor is ignited at various sites by vectors (i.e., woody debris or cones) and then moisture limits the spread of these smoldering ground fires to patches. This linkage between vector fuels and fuel moisture may explain results that have found forest floor consumption beyond moisture thresholds, a common result in research and is reported by managers.

Although considerable effort has been invested in studying the effects of moisture on smoldering combustion of duff, there is little understanding of its role in fire behavior in the forest floor. The inability to model duff smoldering is a major impediment to the restoration and management of fire-prone ecosystems. Our understanding of duff fire spread and consumption patterns lags, in spite of its well-recognized importance in tree mortality, emissions, soil heating, and post-burn spatial heterogeneity. Current empirical models generate binary burn no-burn results based on moisture fraction, measured bulk density, mineral content, and depth. These site specific and environmental condition specific regression models are insufficient for use in other ecosystems and especially to predict duff smoldering behavior across the forest floor. Since forest floor strata are diverse, their presence further complicates modeling; strata have different moisture contents, contain cones and woody fragments that span one or more horizons, and have thus far, been ignored as important fuel strata. Our primary objectives are to better understand the role of fuel moisture relationships on forest floor ignition, spread, intensity, and extinction. The proposed study is focused on the development, parameterization, and validation of a moisture-dependent forest floor fire behavior model that will provide a framework for our scientific investigation and understanding.

Our work improves the understanding of the role of moisture content, presence of vectors, and duff properties in fire spread through the forest floor and evaluating the spatial and temporal variability of duff properties that are important drivers of fire behavior by addressing the following fundamental questions:

1. How does forest floor moisture content influence thresholds of ignition by natural vectors?
2. How does forest floor moisture content influence temperature and duration of smoldering combustion?
3. How does variability in duff composition and spatial location influence ignition probability?
4. How do the above processes interact to generate spatial patterns of forest floor consumption?
5. How do vectors of ignitions (cones) influence duff ignition?
6. How do duff properties (moisture content, depths, and bulk densities) vary spatially in long-unburned sites?

III. Study Description and Location

Study Sites

Field burning experiments were conducted at the Ordway-Swisher Biological Preserve (Ordway) in northern peninsular Florida and at Eglin Air Force Base (Eglin) in the northwestern Florida panhandle. Field experiments evaluating spatial and temporal variability of duff properties were conducted at Ordway. Experimental burns and spatial studies conducted at Ordway were located in xeric long-unburned longleaf pine stands with a patchy midstory of oaks (*Quercus hemisphaerica*, *Q. geminata*, and *Q. laevis*), a thick forest floor, and sparse to no herbaceous vegetation.

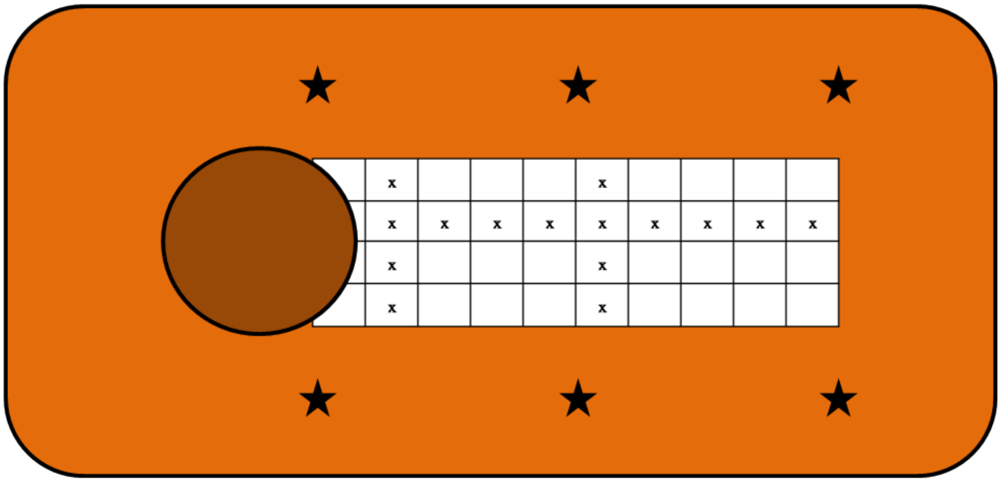
Influence of cones as vectors of duff ignition in laboratory

Eighteen forest floor samples (50×30 cm), extracted from the Ordway-Swisher Biological Preserve, were each divided for burning experiments to evaluate the role of pine cones as a vector for ignition of duff. Nine of the samples were collected from the "tree base" (short end adjacent to tree) and nine were collected from an "open" area (greater than 2 m from nearest tree). Each of the 18 samples was divided into two 25×30 cm samples, and one randomly assigned to be burned with a longleaf pine cone at its surface. Longleaf pine cones for experiments were collected simultaneously from the study site. Litter depth was measured for all samples, and then removed, oven-dried, and replaced onto duff samples after the remaining duff was bathed in water and allowed to dry to a gravimetric moisture content of 60% (ignition threshold observed from our previous experimental burns) just prior to ignition. For those samples assigned a "cone" treatment, one longleaf pine cone (also oven-dried) was placed at the center of the fuel bed. Litter was ignited along the short edge of each fuel bed. For each burn, flame heights, flaming time, and whether duff ignited, was recorded. Model selection criteria (AIC) were used to compare logistic regression models of duff ignition with fuel bed characteristics (litter mass, duff bulk density, and cone presence) as predictor variables. A permutation test showed no significant difference in ignition between tree base and open samples, so this variable was not used in the analysis. Logistic regression models were also compared using flame heights and flaming duration as predictor variables.

Tree scale burns

Plots were oriented on the side of the pine with little woody vegetation present, and with substantial (ca. 15 cm deep) forest floor accumulation. Plots consisted of a 60 × 150 cm grid containing forty 15 × 15 cm cells, surrounded by a 0.5 m raked buffer (Fig. 1). Fuel consumption pins were inserted at corners of all cells flush with the upper surface of the litter. Litter depth was recorded at all pins (generally 52 pins because the base of the tree obstructed cells). Duff (fermentation and humus) and litter depth were measured at six locations along the plot buffer (three on each side of the plot), approximately 25 cm from the edge of plot; these data were used to estimate depths to insert thermocouples. Following burning, fuel depth (top of pin to residual fuel) and soil depth (top of pin to mineral soil) were measured to estimate duff consumption. Plot slope, plot azimuth (from start of plot to tree), and tree dbh were recorded for all plots. The plot design minimized fuel manipulation within the buffer zone and guaranteed no manipulation of duff within the grid prior to burning.

(a)



(b)

Figure 1. Panel (a) shows plot layout. Stars represent fuel measurement locations, while x's mark thermocouple locations. Panel (b) shows Temperature monitoring equipment including large tripod for thermal infrared camera and datalogger with thermocouples.

We assessed temperatures during experimental burns within 1) the duff profile and 2) mineral soil at a depth of 5 cm. Data from fuels measurements were used to calculate average duff thickness and soil depth; these data were used to calculate thermocouple insertion depth to achieve insertion midway in the duff profile (half the total duff thickness) and ca. 5 cm in the mineral soil. Within each plot, 30 Type-K thermocouples were inserted in 15 cells, with one in the duff and one in the soil at each insertion point (Fig. 1). Thermocouples were inserted in a continuous line of cells from the beginning of plot to the tree, and in two rows perpendicular to the tree (Fig. 1). Thermocouples were connected to a Campbell Scientific AM 16/32 relay multiplexer wired to a Campbell Scientific CR1000 datalogger that logged mean and maximum temperature (°C) at one minute intervals throughout burns. Each burn was allowed to progress for ca. 8 h and then extinguished.

To characterize surface temperatures of smoldering combustion at a finer spatial scale, a FLIR SC640 research-grade thermal infrared camera was mounted ca. 5.5 meters above the fuelbed on a custom tripod centered over the plot (Fig. 1). Glowing charcoal pieces were placed 20 cm from each corner of the plot on tins cans for a reference in each image, and thermal infrared images were recorded at one-minute intervals for the duration of each burn. Thermal images were then registered using a projective transformation and the charcoal pieces as reference points. To reduce the impact of any remaining jitter, images were smoothed using a Gaussian kernel. Data from thermocouples and infrared images were analyzed using time series.

Spatial variation of duff characteristics

Three forest stands at the Ordway-Swisher Biological Preserve were used to evaluate spatial variation in duff depths, bulk densities, and moisture contents (Fig. 2). Moisture contents were evaluated across three precipitation scenarios: after a prolonged dry period, after moderate rainfall, after heavy rainfall. Transects were established in each stand that provided a spatial array for duff sampling that included a range of distances between samples of 0.10 m to 105 m. Duff depths and bulk densities were compared between fermentation and humus horizons and their variation compared between horizons at three spatial scales. Also, spatial autocorrelation of these characteristics, by horizon, were determined using the Moran's I statistic. The same analyses were conducted for duff moisture contents, but with the additional factor of precipitation scenarios.

To characterize duff characteristics surrounding individual trees, three mature pines were sampled within each stand on each of the three sampling dates, for a total of 27 trees. Four samples were taken at each tree at 0, 30, 90, and 150 cm from the tree's base in a random orientation. Duff depth, moisture and bulk density were measured for each of these samples and analyzed using ANOVA, where distance from tree and sample date defined the groups.

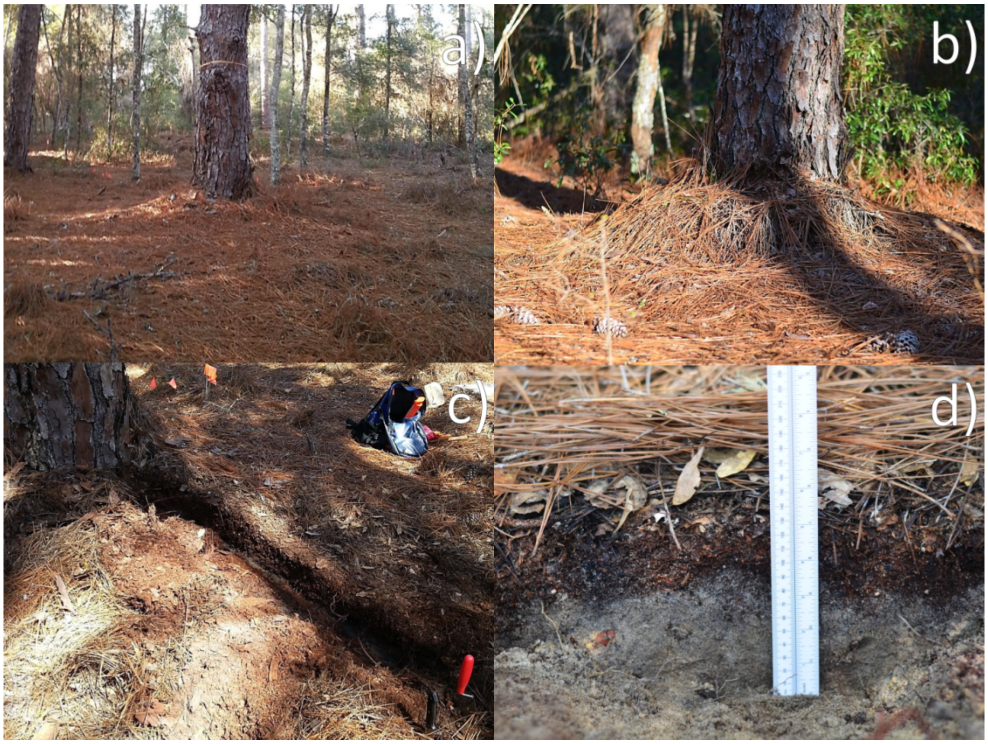


Figure 2. Forest floor of a long-unburned longleaf pine (Pinus palustris) forest at Ordway-Swisher Biological Station in Florida, USA. A pronounced "mound" at the base of mature pines (a & b) were common. Depths of fermentation and humus duff horizons were measured (c & d) and samples were extracted to quantify bulk density and moisture contents.

Duff desorption

Using sixteen of the forest floor samples (45×30 cm) collected at Ordway (eight from tree bases, eight from the open), duff drying was examined using the timelag (response time) concept. Each forest floor sample was split into two 45×15 cm sections, one of which was used for burning experiments (see below) and the other was further split into three 15×15 cm subsamples to evaluate moisture desorption response times. All duff subsamples (48) were bathed beneath an overhead sprinkler for 72 hours and subsequently allowed to dry under laboratory conditions. Samples were weighed periodically and response times were calculated using standard methods.

Frontal heating during smoldering combustion

Using twelve of the 45×15 cm sections split from the above desorption experiments, burning experiments were conducted to evaluate frontal heating ahead of the smoldering combustion. The samples were randomized into three moisture treatments, replicated four times. Four samples were burned under the laboratory dry moisture conditions, while the other eight were soaked beneath an overhead sprinkler for 64 h, then allowed to desorb moisture for eight hours outside under moderate conditions (high temperature ~22.5 °C, dew point 12.8 °C, light winds, partly cloudy to cloudy). Samples were then taken into the lab and allowed to desorb further. Four samples were burned after 45 h of lab drying (53 h total drying) and four samples were burned after 63 h of lab drying (71 h total drying).

Tightly fitting duff samples were placed into 50×15 cm burning boxes to reduce open air flow. Prior to burning, twenty-four Type J (30 AWG) exposed thermocouples were inserted at 10, 20, and 30 cm from the ignition edge of each duff sample (the short 15 cm edge). At each location, two thermocouples were placed in the duff, one 1.5 cm deep from the top (assuming the fermentation horizon), and one 1.5 cm up from the bottom (assuming the humus horizon). Fuelbeds were ignited via first igniting 25 grams of oven-dried long-fibered sphagnum moss packed into the 10 cm in front of the ignition edge of the duff beds and level with the duff. Thermocouples recorded temperatures every 30 sec, while a FLIR T-640 thermal infrared camera was used to record images every 5 min (every minute during the first dry burns).

Mathematical simulation model

A mathematical cellular automaton model was developed to model the horizontal spread of a smoldering duff fire in two dimensions. Campbell at al.'s (1995) model for heat and moisture transport was modified two dimensions and to account for heat and mass loss from the vertical surface. The resulting equations for temperature *T* and volumetric moisture content *θ* are:

$$C\frac{\partial T}{\partial t} - Hd_w\frac{\partial \theta}{\partial t} = \nabla \cdot (K\nabla T) - \kappa_c(T - T_a)$$

$$d_w\frac{\partial \theta}{\partial t} = -\nabla \cdot \left(\frac{V}{1-\frac{p}{P_a}}\nabla p\right) - \frac{\kappa_V(\pi - \theta)M_w}{1-\frac{p}{P_a}}\left(\frac{p}{RT} - \frac{p_a}{RT_a}\right)$$

The burn state of each cell is modeled using one of three states: unburned, burning, and burned. The transition to the burning state is stochastic with a probability that is a logistic function of mineral content, bulk density, and the time-dependent moisture content (similar to Frandsen 1997). Cells transition to the unburned state after an exponentially distributed periods of time.

IV. Key Findings

Influence of cones as vectors of duff ignition

Litter weight positively influenced the probability of duff ignition, while duff bulk density negatively influenced ignition probability. The presence of pine cones, however, overwhelmed ignition probability in these experiments. In stark contrast to fuelbeds without cones, in which duff ignition only occurred in 17% of samples, those with cones added ignited the underlying duff 94% of the time (Fig. 3). Flame heights were 40% taller and flaming duration was 47%

longer the fuel beds with cones. Although confounded with cone presence, flame heights significantly influenced ignition probability. The presence of cones, or other vectors, may be very important for the ignition of duff during prescribed or wild fires. These results were published in Kreye et al. (2013).

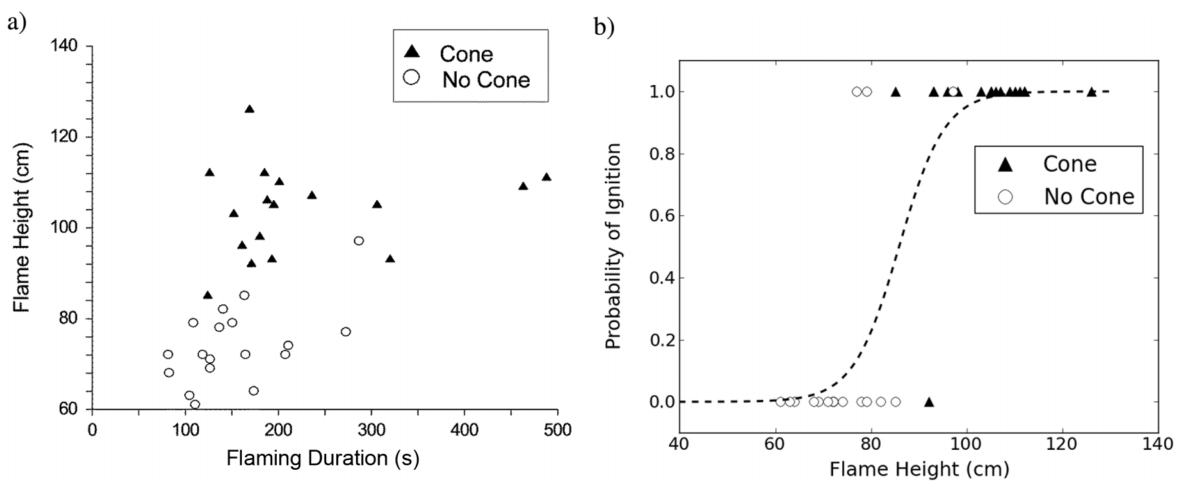


Figure 3. The effects of pine cones on flame height and probability of ignition of forest floor samples (from Kreye et al. 2013)

Tree scale burns

The most important observation obtained from 29 experimental duff burns during 2011 was that duff ignition was most likely to occur within the basal duff mound nearest to the tree (Fig. 4), opposed to the beginning of the plot where the litter was ignited. Of those burns, 13 (45%) trees experience a distribution of consumption that was significantly different from random, 12 (41%) of those experienced more consumption in the third of the plot nearest the tree than expected by random chance (α=0.05 permutation test, see Gill 2012). Lower fermentation horizon moisture content near the tree may explain this phenomenon, as observed in a separate study in this region, see *Spatial variation of duff characteristics* section below. Anecdotally, the apparent greater slope of the basal duff mound may have resulted in greater wind/oxygen availability at the fuelbed surface (Figure 4a).

Infrared thermography predicted consumption at the fuel consumption pins but were insufficient to predict temperature within the duff. A binary logistic regression model for consumption using infrared data only correctly predicted 280 of 364 (ca. 78%) fuel consumption pins correctly. For sites that had non-zero consumption, a linear model provided a reasonable fit of percent consumption using the infrared data. (adjusted R^2 = 0.72; see Fig. 5). In 34 of the 37 time series analyzed, the best fitting model (i.e. lowest AICc) had infrared temperature as a regressor.

However, these models were fit separately for each burn, and the relationship was not consistent across burns.

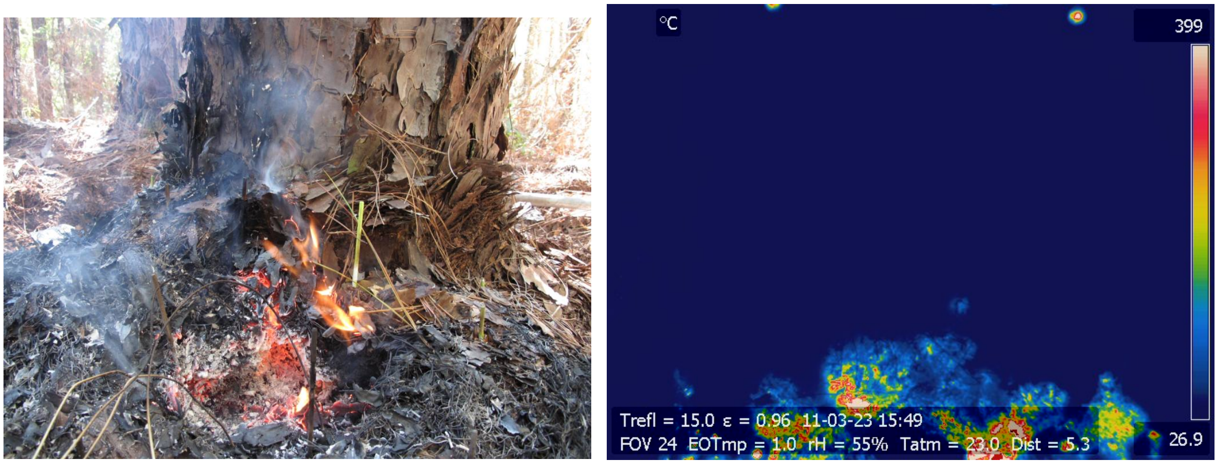


Figure 4. Typical duff ignition at the tree base, within the basal duff mound.

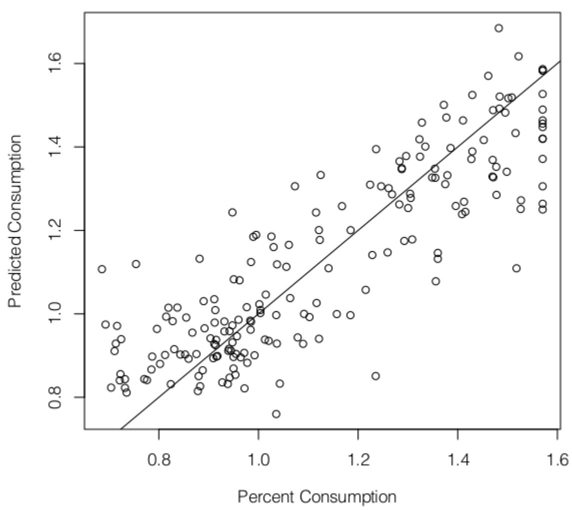


Figure 5. Arcsine transformed fit vs. observed percent forest floor fuel consumption at pins. The prediction consumption was made using thermal infrared data only.

Spatial variation of duff characteristics

With the exception of fermentation moisture content, under moist conditions, duff characteristics were not normally distributed across our sampling locations, with distributions being generally skewed. Fermentation duff horizons were consistently wetter than the underlying humus under the three different moisture conditions (dry, intermediate, and wet; Fig. 6). Fermentation moisture varied more widely than humus, and variability increased under wetter conditions. Humus horizons, however, were deeper and denser than fermentation horizons and also varied more in depth and bulk density.

Duff characteristics varied at fine spatial scales in this study, with depths and bulk densities of both horizons and moisture contents of fermentation layers varying more within stands that across a forest-level scale. Although duff depths varied widely, moderately strong spatial autocorrelation was observed at fine scales (10 m). Fermentation bulk densities were moderately spatial autocorrelated at fine scales, but there was little evidence of autocorrelation in humus. These humus observations are in concert with the much higher variation observed in humus bulk density compared with fermentation bulk densities. Fermentation moisture varied much more than in the underlying humus and this was reflected spatially, where moderate spatial autocorrelation was detected in humus moisture contents yet no spatial autocorrelation was detected in fermentation moisture, highlighting the very fine-scale of moisture variation in the upper duff where ignition is likely to initiate.   These results are included in a manuscript (Kreye, Varner, and Dugaw) accepted pending revisions (07 June 2014) to *Canadian Journal of Forest Research*.

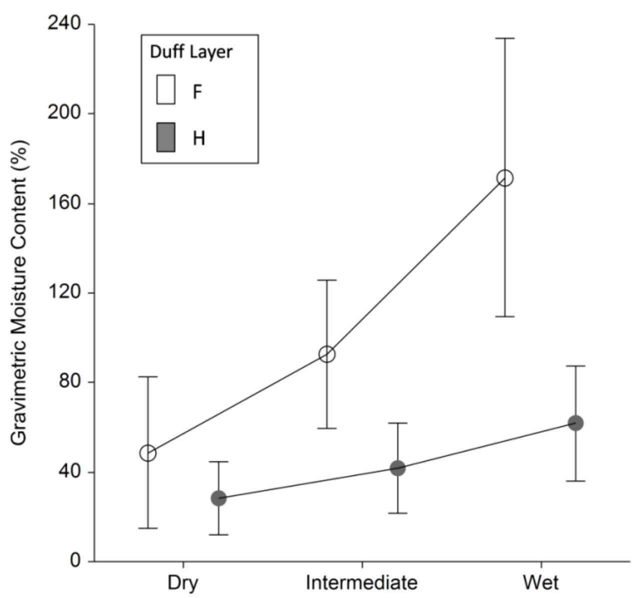


Figure 6. Moisture content variation in fermentation (white circles) and humus (gray circles) forest floor horizons across three different moisture scenarios.

Samples collected near individual pines revealed the variability of duff properties as a function of the distance from tree. Fermentation depth decreased with distance from tree, while fermentation moisture content was significantly lower near the tree base across all sample dates. Bulk density, humus depth, and humus moisture content did not vary significantly with distance from tree for each sample date (all $P > 0.05$).

Duff desorption

Our analysis of duff drying (Fig. 7) depicts typical rapid initial moisture loss followed by reduced rates of water loss over time. As with spatial variation in drying, we found substantial variation in drying across our forest floor samples. Experiments resulted in variable water adsorption, with moisture contents ranging from 64 to 200% ($\bar{x}$=121%, SD=32%). Response times (τ) of duff samples averaged 120 h but ranged widely from 54 to 209 h (SD=43 h). Although moisture adsorption and desorption both varied widely across our samples, they were not related ($P = 0.636$, r = 0.09). Duff depth, which ranged from 5.7 to 11.3 cm, was not a significant predictor of response time ($P = 0.316$), however bulk density, ranging from 0.06 to 0.16 g cm^{-3}, significantly influenced moisture response time ($P = 0.001$). This small-scale variation fits within our field sampling and helps illuminate the mechanisms for the larger-scale patterns observed in our field study and in prescribed and wildfires in the region.

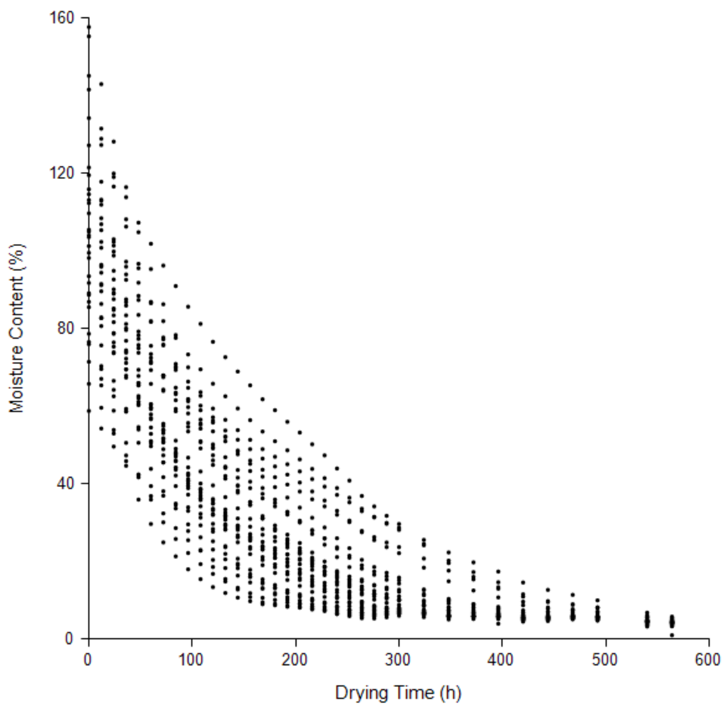


Figure 7. Results of longleaf pine duff moisture drying experiments.

Frontal heating during smoldering combustion

Surface temperatures across burning replicates followed expected patterns, but variation within moisture treatments varied (Fig. 8). Again, this variation helps clarify field observations in fuel consumption variability and the variation in resulting fire effects.

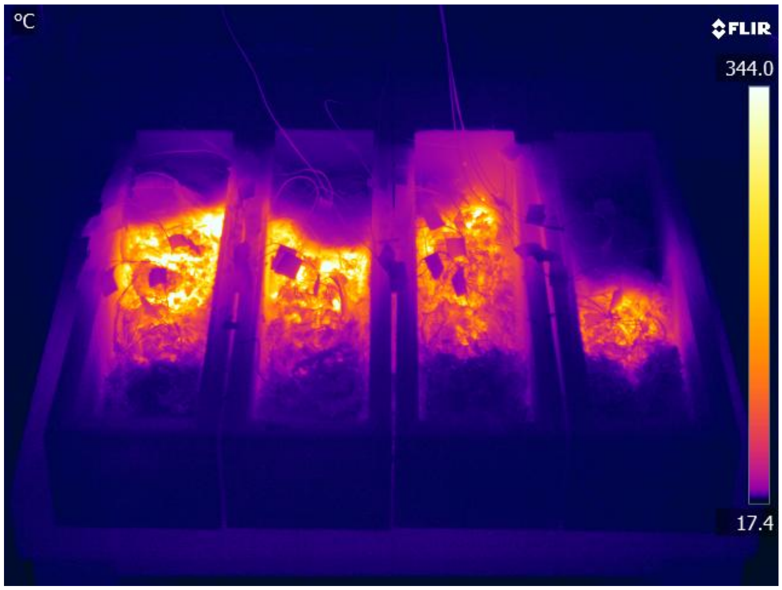


Figure 8. Surface temperatures (vertical bar, °C) of laboratory duff burns. Note variation among boxes, all replicates of the same moisture treatment.

Mathematical simulation model

The model reproduces thresholds of smoldering combustion while making predictions about spatial spread. Specifically, pre-heating and drying is limited to within the 5 cm of the smoldering front (Fig. 9). This result is consistent with our experimental observations (see Fig. 8). Also, there is typically a moisture build-up ahead of the front, which precedes a rapid drying period (see Fig. 10)

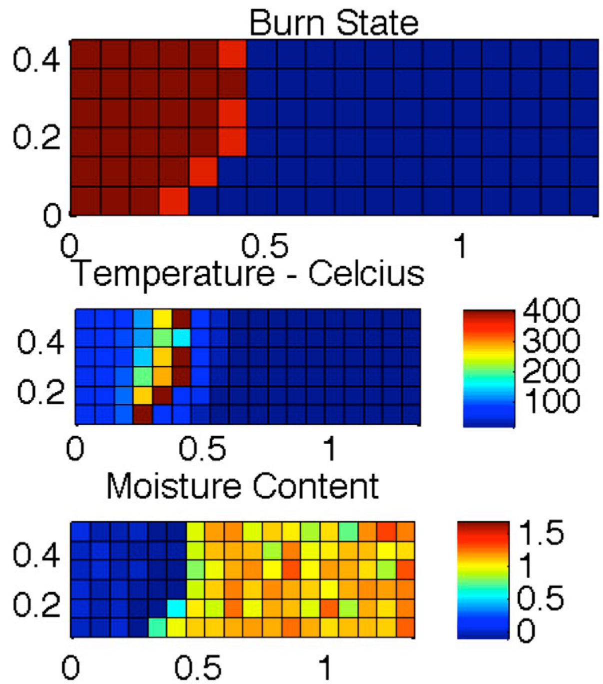


Figure 9. Simulated burn state (blue: unburned, bright red: burning, dark-red: burned), temperature, and volumetric moisture content in a 0.5m ×1.5m plot.

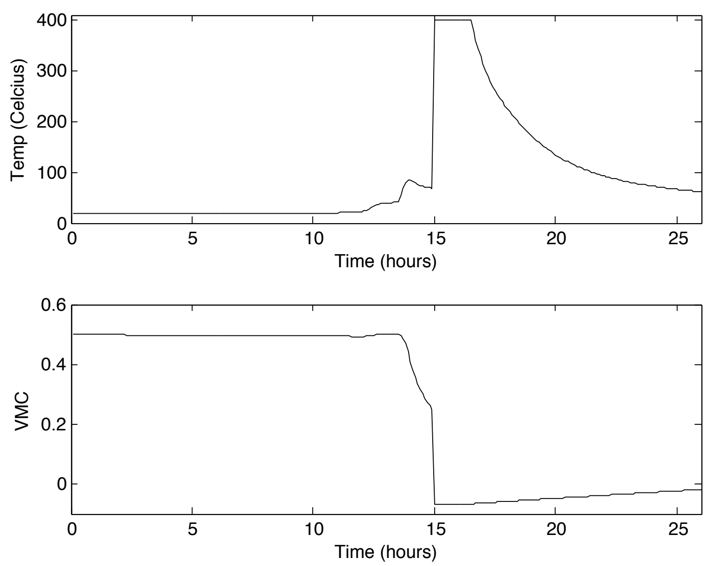


Figure 10. Simulated temperature and volumetric moisture content for a single point in the center of the simulation region.

V. Management Implications

Smoldering fires in forest floor fuels are poorly understood, with high variation in consumption patterns often observed even at fine spatial scales. The ecological consequences of duff fires have been documented, yet their predictability may be difficult given the high spatial variation in duff characteristics. Attention may need to be taken with regard to the heterogeneity of duff conditions, especially moisture content, when planning and implementing prescribed burns in long-unburned longleaf pine ecosystems. While upper duff may wet following precipitation, the spatial variability may be high and, more importantly, the underlying humus may still be dry. The role of cones, and potentially other woody debris, on the forest floor may provide vectors of ignition in fermentation that would otherwise not ignite. Where underlying humus is drier, the extent to which smoldering fires may burn and the level of duff consumption likely to occur may be greater than anticipated when evaluating moisture levels of the upper duff. These deeper and denser humus fuels are likely to be where fine roots have established in long-unburned forests and where undesired fire effects may ensue as a result of long-durations of smoldering combustion. Furthermore, our observed differences in ignition and duff moisture at the tree base warrant careful consideration when planning fires in long-unburned regions.

VI. Relationship to Other findings

- Increasingly infrared thermography is being recognized as a powerful tool for characterizing surface fires (Hiers et al. 2009). Our work suggests that this tool will be useful to monitor duff consumption, but may be limited in its ability to measure duff heating.
- The findings of this project complement recent (Banwell et al. 2013; Banwell and Varner 2014) findings from Jeffrey pine- white fir forests of the Sierra Nevada. From these and past studies we are generating a more complete understanding of the structure, composition, and dynamics of forest floor fuels in long-unburned forests. However, Banwell et al. (2013) found elevated duff moisture at the tree base in contrast to our findings. This difference may be attributed to the differences in crown morphologies of the tree species.
- The results of the spatial variation of duff characteristics provide a potential explination the observed patchy distribution of duff consumption observed by Myanishi and Johnson (2002).
- The study of duff ignition by pine cones demonstrated the plausibility of the theory of vectored ignition first posed by Fonda and Varner (2004).

VII. Future Work

- Further study and analysis of the frontal heating of smoldering duff may provide more insights and comparisons to the smoldering model.
- Given the observed spatial patterns in consumption and moisture, research that links the source of moisture: rainfall, throughfall, and stemflow to near-tree dynamics is warranted.
- Work that investigates the broader impacts of fire exclusion and reintroduction of fire on plant and animal biodiversity is needed.
- Studies that tie the spatial patterns of litter (load and composition) to fire behavior and effects- in sites with and without past fire exclusion could provide practical information to land managers.
- Field drying experiments to tease out horizon and inter-horizon (fuelbed) effects on drying and wetting would provide a better understanding of forest floor fuel moisture dynamics.

VIII. Deliverables

Proposed	Delivered	Status
Publications (4 submission ready manuscripts)	*Pine cones facilitate ignition of forest floor duff* (Canadian Journal of Forest Research)	Published 2013
	Towards a mechanism for eastern North American forest mesophication: differential litter drying across 17 species (Ecological Applications)	Published 2013
	Utility of an instantaneous moisture meter for duff moisture prediction in long-unburned longleaf pine forests (Southern Journal of Applied Forestry)	Published 2013
	Spatial and temporal variability of forest floor duff: autocorrelation and scales of importance (Canadian Journal of Forest Research)	Accepted pending revisions (6/07/2014)
Presentations (none proposed)	*Eight presentations delivered:* *IAWF 4th Fire Behavior Conference (4); Large Wildland Fires Conference (1); 92nd National Convention of Society of American Foresters (1); 5th International Fire Ecology and Management Congress (1); Society for Ecological Restoration World Conference (1).*	Completed in 2013 and 2014.
Website	*http://humboldt.edu/duff/*	Complete
Master's Thesis (1)	*Analysis of Field Data and Spatial Methods for the Parameterization of a Spatial Duff Consumption Model* (Gill, 2012, Humboldt State University)	Completed 2012
Symposium	Special Session at the *Fourth Fire Behavior and Fuels Conference*, Raleigh, NC.	Completed in 2013.
Field Tour (1)	Two field tours at the Ordway-Swisher Biological Field Station: *Prescribed Fire Training Center* (2011); *Alachua Conservation Trust* (NGO; 2011); and informal tour for scientists and managers from the *University of Florida and The Nature Conservancy* (FL chapter; 2012).	Completed in 2012

IX. References

Deliverables

"Spatial and temporal variability of forest floor duff characteristics in long-unburned Pinus palustris forests." Kreye, J.K., Varner, J.M., Dugaw, C. J. *Canadian Journal of Forest Research,* Accepted pending revisions (06/07/2014).

"Spatial and temporal variability of forest floor duff characteristics in long-unburned *Pinus palustris forests*." Kreye, J.K., Varner, J.M., Dugaw, C.J. Poster presentation at the Association for Fire Ecology and International Association of Wildland Fire's Large Wildland Fires: Social, Political, & Ecological Effects Conference. Missoula, MT May 19-23, 2014.

"The role of cones as vectors for duff ignition." Kreye, J.K., Varner, J.M., Dugaw, C.J., Cao, J., Szecsei, J., Engber, E.A. Poster presentation at the Association for Fire Ecology and International Association of Wildland Fire's Large Wildland Fires: Social, Political, & Ecological Effects Conference. Missoula, MT May 19-23, 2014.

"Toward a mechanism for eastern North American forest mesophication: differential litter drying across 17 species." Kreye, J.K., Varner, J.M., Mola, J. *Ecological Applications* 23 (8), 1976-1986, 2013.

"Pine cones facilitate ignition of forest floor duff." Kreye, J.K., Varner, J.M., Dugaw, C.J., Cao, J., Szecsei, J., Engber, E.A., *Canadian Journal of Forest Research* 43 (5), 512-516, 2013.

"Utility of an instantaneous moisture meter for duff moisture prediction in long-unburned longleaf pine forests." Engber, E. A., Varner, J. M., Dugaw, C.J., Quinn-Davidson, L., Hiers, J. K. Southern Journal of Applied Forestry, 37(1), 13-17, 2013.

"Towards a mechanism for eastern deciduous forest mesophication: the role of litter drying." Kreye, J.K., Varner, J.M., Hiers, J.K., Mola, J. Poster presentation at the 92nd National Convention of the Society of American Foresters: Silviculture Matters. Charleston, SC Oct 23-27, 2013.

"Ecological consequences of fire exclusion in longleaf pinelands of the southeastern US." Varner, J.M., L. Kobziar, A.J. Long, and W.J. Platt. Oral presentation in an organized Special Session at the Society for Ecological Restoration's Fifth World Conference, Madison, WI Oct 6-11, 2013.

"Linking Smoldering Duff Temperatures to Surface Thermal Infrared Images." Cao, J., Oral presentation at the 4th Fire Behavior and Fuels Conference. Raleigh, NC Feb 18-22, 2013.

"Modeling Smoldering Combustion of Forest Duff." Dugaw, C.J., Oral presentation at the 4th Fire Behavior and Fuels Conference. Raleigh, NC Feb 18-22, 2013.

"Ecological consequences of smoldering fires in long-unburned longleaf pine forests." Varner, J.M., Oral presentation at the 4th Fire Behavior and Fuels Conference. Raleigh, NC Feb 18-22, 2013.

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