fire

Communication

Assessing the Relationship between Litter + Duff Consumption and Post-Fire Soil Temperature Regimes

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Abstract: The immediate effects of wildland fire on soil have been well documented. However, we know much less about the longer-term effects and their implications for plants. Post-fire soil temperature regimes, for example, have received relatively little research attention, despite potential effects on plant phenology and establishment. Using portable temperature datalogger units (iButtons), we conducted an experimental study to assess how fire severity (measured in terms of litter and duff consumption) influences biologically relevant temperature parameters such as diel minimums, maximums, means, and ranges. We also used these data to calculate cumulative soil growing degree days (GDDs). The study was conducted during the early to mid-spring to capture the transition from dormant season to growing season. Results indicate that mean and max soil temperatures increase in the weeks after fire, with the most pronounced effects in the higher severity treatments. By the end of the 40-day study period, soils in the high severity burn treatment had accumulated 72 GDDs, compared to 17.9, 13.6, and 1.4 in moderate, low, and control treatments, respectively. These findings indicate that fire severity has significant and persistent effects on post-fire soil temperature regimes, and this likely has implications for the post-fire vegetation response.

Keywords: duff; fire severity; litter; phenology; prescribed fire; soil temperature; wildfire

1. Introduction

Fire has historically been an essential component of the disturbance regime in many forest ecosystems [1–3]. Along with reducing hazardous fuel loads, it encourages the regeneration of fire-adapted species, constrains the spread of fire-sensitive species, and can result in increases in plant species richness [4–9]. Fire can also influence plant phenology by inducing budding and modifying the timing abundance of flower and fruit production [10,11]. Seed germination for some species is stimulated by fire [12] and/or may be enhanced by a warmer post-fire environment [11,13].

Fire behavior is heavily dependent on the type and amount of fuel available, and fires that heavily impact surface fuels can have implications for soil properties [14–17]. Potential changes to burned soil such as reduced productivity and increased sedimentation can impact a multitude of ecosystem services including plant production and water quality [18–20]. During severe fires, duff and litter can be completely consumed, which exposes the mineral soil to heating during the fire itself [18]. Burned soils can influence vegetation regeneration, species composition, and forest growth and development [20]. Prolonged soil heating due to smoldering in areas with high accumulations of duff has been implicated in overstory mortality [17,21]. It can also have an impact on grass and forb communities due to direct mortality of established plants or seedbank destruction [22], or by encouraging the germination of seeds from a long-dormant seedbank [23].

While the effects of soil heating during fires are increasingly well-understood, little is known about how litter and duff consumption by fire can influence post-fire soil temperature regimes. The presence of a moist litter and duff layer insulates the mineral soil from high temperatures experienced during fire [16]. Soil structure and organic matter content changes as soil temperature rises above 300 °C, potentially decreasing the amount of water retained by the soil [24]. As soil becomes dryer, the temperature increases and decreases more drastically, since water has a very high specific heat [25]. Additionally, changes in soil albedo, caused by fire, can also influence temperature regimes, as a layer of blackened/charred material will absorb more incident radiation [26,27].

Soil temperature is important as it regulates many important biochemical and biogeochemical processes. For example, soil temperature influences seed germination rates and time of germination, with the seeds of many species not germinating or breaking dormancy until a threshold of cumulative soil heating has been met [13,28–30]. There have been few studies on the post-fire alteration of soil temperature regimes [13,29,31]. These studies, from Australian eucalyptus forests and Mediterranean shrubland, suggest that soil may experience altered temperature regimes post-fire. Specifically, they found that post-fire, mean daily maximum temperatures are higher than on unburnt sites while mean daily minimum temperatures are similar or slightly lower [10,13]. This larger range of post fire soil temperatures caused a greater percentage of seeds to germinate and plays a fundamental role in breaking seed dormancy [29]. More research, however, is needed—particularly across the gradients of fire severity that often distinguish prescribed fire from wildfires.

To improve our understanding of the belowground effects of fire, we conducted a controlled experiment to assess the relationships between fire severity and post-fire soil temperature. The objectives of this study were to assess the feasibility of using small portable datalogger/temperature sensor units (iButtons; Thermochron, Baulkham Hills, NSW, Australia) for measuring soil temperatures post-fire and determine how fire severity influences post-fire soil temperature regimes. iButttons have emerged as cost-effective and easily deployable tools for measuring environmental temperatures [32–35], but have not been extensively used in fire studies. Here, we focus on how fire severity, measured in terms of litter and duff consumption, influences temperature parameters that have implications for plant growth and phenology.

2. Materials and Methods

This study was from 29 February to 8 April 2020. This timeframe roughly corresponds to the dormant season-growing season transition period for most plants in the southern Appalachian/Piedmont region (South Carolina, U.S.A.) where the study was conducted (34°41′20.3′′ N 82°52′09.1′′ W). Mean atmospheric temperatures during the study period ranged from 23 °C to 6 °C [36]. Data from a nearby (~2 km) weather station indicated a total of 11.7 cm of rainfall during the study period, from 5 rainfall events. Rainfall events were separated on average by 4.5 rain-free days.

Sixteen 23 cm × 33 cm × 6 cm stainless steel pans had four holes drilled in the bottom of them to facilitate water drainage. Holes were drilled on the edge of the pan at the halfway point between each corner. Each pan was then painted white, avoiding the bottom of the pans, to ensure that the metal absorbed as little heat as possible. Each pan was filled with a 2 cm base of damp "natural" colored play sand as a uniform mineral soil medium similar to the sandy loam topsoil of the study region [37]. A 4.5 cm layer of litter and duff was placed on top of the mineral soil medium. Duff was not incorporated into the mineral soil so as to simulate the "mat" of mor-humus that would naturally occur in xeric sites in the study region. The litter and duff were collected from a mixed pine-hardwood stand containing mostly loblolly pine (*Pinus taeda* L.) and several upland oak species (*Quercus* spp.). The litter and duff of each tray was then burned for increasing amounts of time [15] to create a range of fire severity classes (Figure 1) using a handheld garden torch (Figure 2a):

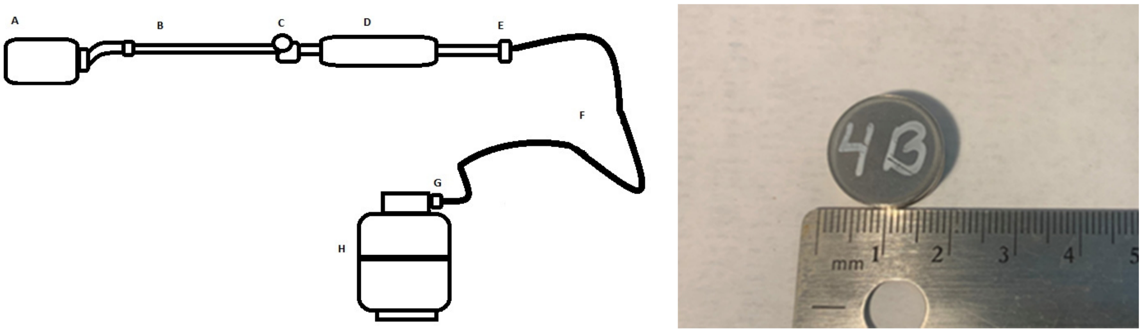
0: Control—no burn.

1: Low—litter charred to partially consumed and no changes to duff.

2: Moderate—litter is almost completely consumed with ash and a charred duff layer; some fine woody fuels may remain.

3: High—complete consumption of all litter, duff and fine woody fuels.

Figure 1. Image of the four experimental treatments. Left to right: unburned control; level 1 = low severity; level 2 = moderate severity; level 3 = high severity. There were 4 replicates of each treatment (n = 16).



(**a**) (**b**)

Figure 2. (**a**) A schematic of the propane torch, showing the torch head (A), neck tube (B), pilot valve (C), handle (D), hose connection (E), hose (F), pressure regulator (G), and propane tank (H). (**b**) An iButton temperature sensor. Sensors were buried in mineral soil below the litter/duff and programmed to log temperatures (Celsius) in 10 min intervals during the 40-day study period.

There were four replicates of each of the four severity classes. After the burning treatment, each tray had one iButton sensor, model DS1922L-F50, (Figure 2b) placed 0.5 cm into the sand layer and re-covered with the litter and duff layer. A cover for each tray was made with white chicken wire to prevent wind or wildlife from removing any of the litter layer from the trays or disturbing the sensor. The trays were then placed in two rows in an open field where they would receive full sun and be exposed to the elements. iButton sensors were programmed to record temperature in °C every 10 min.

Statistical Methods

Upon conclusion of the study period, data were downloaded and summary statistics for ecologically relevant temperature parameters (diel mean, maximum, minimum, range) were calculated. Additionally, soil growing degree days (GDDs) were calculated for each 24-h period using the following formula, with negative GDD values converted to zeros:

$$GDD = \frac{Maximum\ temperature\ (C) + minimum\ temperature\ (C)}{2} - 10\ ^{\circ}\mathrm{C}$$

An Analysis of Variance (ANOVA) was conducted on 4 temperature parameters (max, mean, minimum, range) for each day of the study period in JMP v. 14.43 (SAS, Cary NC, USA). Data for soil GDDs were compared on a cumulative basis, while all other temperature parameters were compared on a diel (24 h) basis. Differences between treatments were declared statistically significant at $\alpha = 0.05$, and pairwise tests (Tukey's HSD) were conducted when the ANOVA indicated a significant treatment effect.

3. Results

Soil temperature profiles from the iButton sensors illustrated diel temperature fluctuations that reflected local weather conditions (Figure 3; Figure S1). Increases in fire severity resulted in greater mean soil temperatures post-fire, and greater diel temperature fluctuations. Significant treatment effects for mean, maximum, minimum, and range were observed on 27, 40, 17, and 39 out of 40-days, respectively, with treatment effects typically being significant and most pronounced on days without rainfall. The control treatment was significantly different from all other treatments on most days, temperature parameters for low and moderate severity treatments were generally similar, and the high severity treatment experienced the greatest temperature fluctuations and had the highest mean temperatures.

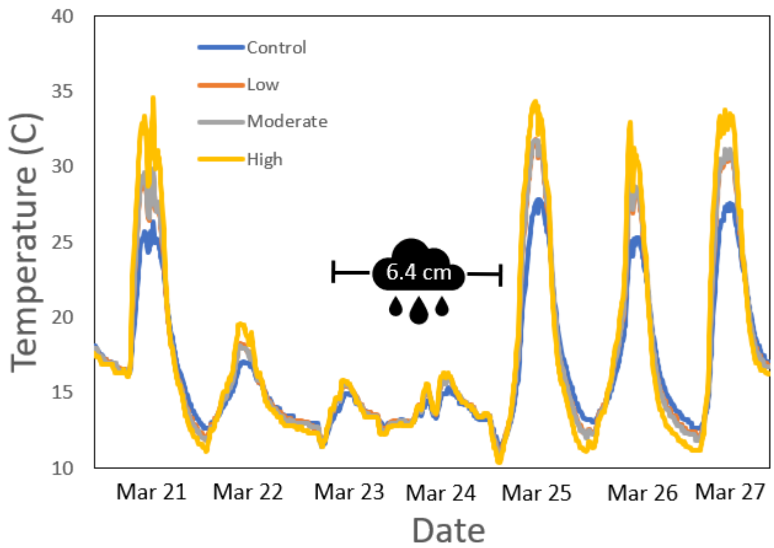


Figure 3. iButton temperature readouts for each of the 4 experimental treatments (unburned control; level 1 = low severity; level 2 = moderate severity; level 3 = high severity) during a portion of the study period. A significant multi-day rain event occurred between 3/23 and 3/25. See supplemental table for the data from the entire study period, including Analysis of Variance (ANOVA) and pairwise comparison results.

Cumulative soil GDDs generally increased with increasing fire severity. At the end of the study period, cumulative soil GDDs were 1.4, 13.6, 17.9, and 72.0 in control, low severity, moderate severity, and high severity treatments, respectively (Figure 4). These differences were statistically significant ($P = 0.001$), with high severity being significantly greater than all other treatments, moderate and low severity being similar, and control being lowest.

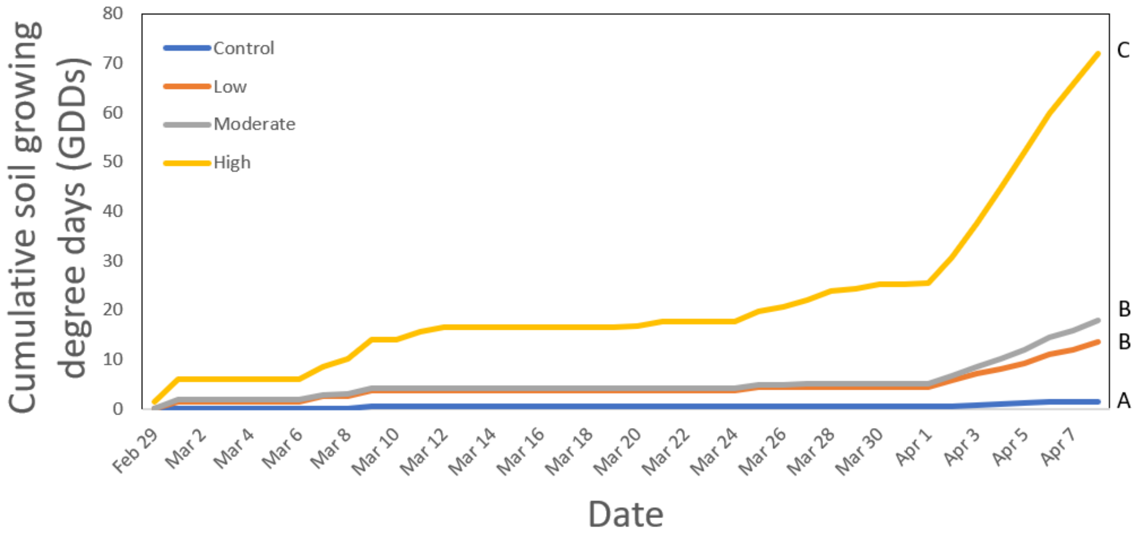


Figure 4. Cumulative soil growing degree days (GDDs) for each of the 4 experimental treatments (unburned control; level 1 = low severity; level 2 = moderate severity; level 3 = high severity) during the study period. Treatments with different uppercase letters had significant differences ($\alpha = 0.05$) for cumulative soil GDDs at the end of the study period.

4. Discussion

The partial or complete removal of the duff and litter layer during a fire coupled with the deposition of low-albedo charcoal will lead to increased soil temperatures post-fire [29,38]. Increased soil temperatures post-fire can have an ecologically significant impact on soil due to an increase of evaporation rates and increased mineralization of soil organic matter [31]. Additionally, long duration mineral soil heating causes a loss in coarse root carbohydrates which leads to overstory tree stress [21]. These combined factors can cause post-fire tree decline by decreasing radial growth [21]. The apparent relationship between rainfall and soil heating underscores the importance of water in moderating soil temperatures [39]. In the absence of a water-retaining litter and duff layer, soils in the high severity treatment experienced dramatic post-fire temperature fluctuations and accumulated significantly more heat (soil GDDs) over time. Growing degree days (GDD) are a measure of heat accumulation that has implications for the timing of dormancy breaking for many plant species [40]. This pattern was strongest towards the end of the study period (late March/early April), which corresponds to the time period when many plants would be beginning to break dormancy.

Plant phenology is influenced by several factors: most notably temperature variations during the winter-spring and fall-winter transitions [41]. Spring blooming is occurring earlier and has been largely attributed to increases in air temperature [42]. Increased air temperatures cause increased soil temperatures after a fire [28]. Earlier spring brought on by warmer temperatures enhances evapotranspiration rates which removes soil water earlier in the growing season [42]. Post-fire, the amount of solar radiation reaching the forest floor, is increased, which in turn increases evaporation rates and alters thermal properties of the soil [29,31]. As soil water reserves are depleted, photosynthesis is inhibited, and net carbon uptake is reduced [42].

Higher temperatures near the soil surface can also aid in breaking dormancy of hard-coated seeds, stimulating seedling emergence [29]. Thus, post-fire soil heating has the potential to significantly influence plant phenology, with plants likely breaking dormancy earlier following fires that result in substantial litter and duff removal [43,44]. Further, it stands to reason that seeds in a relict seedbank that do not germinate following a typical low-severity fire would perhaps break dormancy following a more severe fire [45,46], provided that those seeds were not damaged or consumed during the fire. Indeed, studies have shown that low severity prescribed fires that leave duff intact often do not generate a strong response from understory graminoids and forbs [47,48]. While there are many possible explanations for this, our study suggests that such fires may not influence post-fire soil temperatures in a manner that would stimulate germination. If higher severity prescribed fires are not feasible, repeated lower severity burns that incrementally reduce litter and duff thickness could be effective.

5. Conclusions

While we acknowledge that the experimental conditions in this study may not precisely reflect actual conditions that would occur in a forested environment, the findings nonetheless illustrate a strong relationship between litter and duff consumption and post-fire soil temperature regimes. With increasing degrees of litter and duff consumption, we observed significant and persistent increases in soil temperatures post-fire. These effects are likely biologically significant, considering the importance of temperature—particularly soil temperature—in regulating plant phenology. Understanding the longer-term impacts of fire on soil temperature, along with the associated implications for plants, will aid in our ability to predict how forests will respond to wildfire and prescribed fire. Additionally, this study highlights the potential utility of iButton temperature loggers for deriving ecologically useful temperature parameters for soil and fire research.

Supplementary Materials: The following is available online at http://www.mdpi.com/2571-6255/3/4/64/s1, Figure S1: Summary temperature statistics (mean, max, min, range), collected with iButton temperature loggers in 4 experimental burn severity treatments (control, level 1 (low), level 2 (moderate), level 3 (high)) over a 40-day period. There were 4 replicates for each treatment (n = 16). Rainfall events are marked in blue, with total daily rainfall (cm) listed. Results with different uppercase letters, for a given parameter on a given day, were statistically different at $\alpha = 0.05$.

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References

1. Agee, J.K. The Landscape Ecology of Western Forest Fire Regimes. *Northwest Sci.* **1998**, *72*, 24–34.
2. Knapp, E.E.; Estes, B.L.; Skinner, C.N. *Ecological Effects of Prescribed Fire Season: A Literature Review and Synthesis for Managers*; U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: Albany, CA, USA, 2009; p. 5.
3. van Lear, D.H.; Waldrop, T.A. *History, Uses, and Effects of Fire in the Appalachians*; U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: Asheville, NC, USA, 1989; pp. 1–3.
4. Hollingsworth, T.N.; Johnstone, J.F.; Bernhardt, E.L.; Chapin, F.S. Fire Severity Filters Regeneration Traits to Shape Community Assembly in Alaska's Boreal Forest. *PLoS ONE* **2013**, *8*, e56033. [CrossRef]
5. Johnstone, J.F.; Chapin III, F.S.; Foote, J.; Kemmett, S.; Price, K.; Viereck, L. Decadal observations of tree regeneration following fire in boreal forests. *Can. J. For. Res.* **2004**, *34*, 267–273. [CrossRef]
6. Reich, P.B.; Abrams, M.D.; Ellsworth, D.S.; Kruger, E.L.; Tabone, T.J. Fire Affects Ecophysiology and Community Dynamics of Central Wisconsin Oak Forest Regeneration. *Ecology* **1990**, *71*, 2179–2190. [CrossRef]
7. Reilly, M.J.; Wimberly, M.C.; Newell, C.L. Wildfire Effects on Plant Species Richness at Multiple spatial Scales in Forest Communities of the Southern Appalachians. *J. Ecol.* **2006**, *94*, 118–130. [CrossRef]
8. van Lear, D.H.; Waldrop, T.A. Effect of Fire on Natural Hardwood Regeneration in the Appalachian Mountains. In *Proceedings: Guidelines for Regenerating Appalachian Hardwood Stands*; Smith, H.C., Perkey, A.W., Kidd, W.E., Jr., Eds.; SAF Publication 88-03; West Virginia University Books: Morgantown, WV, USA, 1988; pp. 56–70.

9. Wan, H.Y.; Olson, A.C.; Muncey, K.D.; St. Clair, S.B. Legacy effects of fire size and severity on forest regeneration, recruitment, and wildlife activity in aspen forests. *For. Ecol. Manag.* **2014**, *329*, 59–68. [CrossRef]
10. Kaplan, D.; Gutman, M. Phenology of Quercus ithaburensis with emphasis on the effect of fire. *For. Ecol. Manag.* **1999**, *10*, 61–70. [CrossRef]
11. Paritsis, J.; Raffaele, E.; Veblen, T.T. Vegetation disturbance by fire affects plant reproductive phenology in a shrubland community in northwestern Patagonia, Argentina. *N. Zeal. J. Ecol.* **2006**, *30*, 387–395.
12. Cushwa, C.T.; Martin, R.E.; Miller, R.L. The Effects of Fire on Seed Germination. *J. Range Manag.* **1968**, *21*, 250. [CrossRef]
13. Baeza, M.J.; Roy, J. Germination of an obligate seeder (Ulex parviflorus) and consequences for wildfire management. *For. Ecol. Manag.* **2008**, *256*, 685–693. [CrossRef]
14. Garlough, E.C.; Keyes, C.R. Influences of moisture content, mineral content and bulk density on smouldering combustion of ponderosa pine duff mounds. *Int. J. Wildland Fire* **2011**, *20*, 589. [CrossRef]
15. Klimas, K.; Hiesl, P.; Hagan, D.; Park, D. Prescribed fire effects on sediment and nutrient exports in forested environments: A review. *J. Environ. Qual.* **2020**, *49*, 793–811. [CrossRef]
16. Valette, J.; Gomendy, V.; Marechal, J.; Houssard, C.; Gillon, D. Heat-Transfer in the Soil during Very Low-Intensity Experimental Fires—The Role of Duff and Soil-Moisture Content. *Int. J. Wildland Fire* **1994**, *4*, 225. [CrossRef]
17. Varner, J.M.; Hiers, J.K.; Ottmar, R.D.; Gordon, D.R.; Putz, F.E.; Wade, D.D. Overstory tree mortality resulting from reintroducing fire to long-unburned longleaf pine forests: The importance of duff moisture. *Can. J. For. Res.* **2007**, *37*, 1349–1358. [CrossRef]
18. Hahn, G.E.; Coates, T.A.; Latham, R.E.; Majidzadeh, H. Prescribed Fire Effects on Water Quality and Freshwater Ecosystems in Moist-Temperate Eastern North America. *Nat. Areas J.* **2019**, *39*, 46. [CrossRef]
19. Klimas, K.; Hiesl, P.; Hagan, D.; Park, D. Burn Severity Effects on Sediment and Nutrient Exports from Southeastern Forests Using Simulated Rainfall. *For. Sci.* **2020**, fxaa029. [CrossRef]
20. Jain, T.B.; Pilliod, D.S.; Graham, R.T.; Lentile, L.B.; Sandquist, J.E. Index for Characterizing Post-Fire Soil Environments in Temperate Coniferous Forests. *Forests* **2012**, *3*, 445–466. [CrossRef]
21. Varner, M.J.; Putz, F.E.; O'Brien, J.J.; Kevin Hiers, J.; Mitchell, R.J.; Gordon, D.R. Post-fire tree stress and growth following smoldering duff fires. *For. Ecol. Manag.* **2009**, *258*, 2467–2474. [CrossRef]
22. Kreye, J.K.; Varner, J.M.; Kobziar, L.N. Long-Duration Soil Heating Resulting from Forest Floor Duff Smoldering in Longleaf Pine Ecosystems. *For. Sci.* **2020**, *66*, 291–303. [CrossRef]
23. Willson, K.G.; Barefoot, C.R.; Hart, J.L.; Schweitzer, C.J.; Dey, D.C. Temporal patterns of ground flora response to fire in thinned Pinus—Quercus stands. *Can. J. For. Res.* **2018**, *48*, 1171–1183. [CrossRef]
24. Stoof, C.R.; Wesseling, J.G.; Ritsema, C.J. Effects of fire and ash on soil water retention. *Geoderma* **2010**, *159*, 276–285. [CrossRef]
25. Cary, J.W. The drying of soil: Thermal regimes and ambient pressures. *Agric. Meteorol.* **1967**, *4*, 353–365. [CrossRef]
26. Post, D.F.; Fimbres, A.; Matthias, A.D.; Sano, E.E.; Accioly, L.; Batchily, A.K.; Ferreira, L.G. Predicting Soil Albedo from Soil Color and Spectral Reflectance Data. *Soil Sci. Soc. Am. J.* **2000**, *64*, 1027–1034. [CrossRef]
27. Wondafrash, T.T.; Sancho, I.M.; Miguel, V.G.; Serrano, R.E. Relationship between Soil Color And Temperature In The Surface Horizon Of Mediterranean Soils: A Laboratory Study. *Soil Sci.* **2005**, *170*, 495–503. [CrossRef]
28. Mallek, S.B.; Prather, T.S.; Stapleton, J.J. Interaction effects of Allium spp. residues, concentrations and soil temperature on seed germination of four weedy plant species. *Appl. Soil Ecol.* **2007**, *37*, 233–239. [CrossRef]
29. Santana, V.M.; Bradstock, R.A.; Ooi, M.K.J.; Denham, A.J.; Auld, T.D.; Baeza, M.J. Effects of soil temperature regimes after fire on seed dormancy and germination in six Australian Fabaceae species. *Aust. J. Bot.* **2010**, *58*, 539. [CrossRef]
30. Thompson, K.; Grime, J.P.; Mason, G. Seed germination in response to diurnal fluctuations of temperature. *Nature* **1977**, *267*, 147–149. [CrossRef]
31. Raison, R.; Woods, P.; Jakobsen, B.; Bary, G. Soil temperatures during and following low-intensity prescribed burning in a Eucalyptus pauciflora forest. *Soil Res.* **1986**, *24*, 33. [CrossRef]
32. Fawcett, S.; Sistla, S.; Dacosta-Calheiros, M.; Kahraman, A.; Reznicek, A.A.; Rosenberg, R.; Wettberg, E.J.B. Tracking microhabitat temperature variation with iButton data loggers. *Appl. Plant Sci.* **2019**, *7*, e01237. [CrossRef] [PubMed]

33. Gehrig-Fasel, J.; Guisan, A.; Zimmermann, N.E. Evaluating thermal treeline indicators based on air and soil temperature using an air-to-soil temperature transfer model. *Ecol. Modell.* **2008**, *213*, 345–355. [CrossRef]
34. Robinson, S.I.; McLaughlin, Ó.B.; Marteinsdóttir, B.; O'Gorman, E.J. Soil temperature effects on the structure and diversity of plant and invertebrate communities in a natural warming experiment. *J. Anim. Ecol.* **2018**, *87*, 634–646. [CrossRef]
35. Salisbury, A.; Stolt, M.H. Estuarine Subaqueous Soil Temperature. *Soil Sci. Soc. Am. J.* **2011**, *75*, 1584–1587. [CrossRef]
36. Interagency Fire Center. Andrew Pickens South Carolina. Available online: https://wrcc.dri.edu/cgi-bin/rawMAIN.pl?laSANP (accessed on 11 May 2020).
37. Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online: http://websoilsurvey.sc.egov.usda.gov/ (accessed on 11 February 2020).
38. Iverson, L.R.; Huchinson, T.F. Soil temperature and moisture fluctuations during and after prescribed fire in mixed-oak forests, USA. *Nat. Areas J.* **2002**, *2*, 296–304.
39. Abu-Hamdeh, N.H. Thermal properties of soils as affected by density and water content. *Biosyst. Eng.* **2003**, 97–102. [CrossRef]
40. Kucharik, C.J.; Barford, C.C.; Maayar, M.E.; Wofsy, S.C.; Monson, R.K.; Baldocchi, D.D. A multiyear evaluation of a Dynamic Global Vegetation Model at three AmeriFlux forest sites: Vegetation structure, phenology, soil temperature, and CO_2 and H_2O vapor exchange. *Ecol. Modell.* **2006**, *196*, 1–31. [CrossRef]
41. Schwartz, M.D.; Reiter, B.E. Changes in North American spring. *Int. J. Climatol.* **2000**, *20*, 929–932. [CrossRef]
42. Richardson, A.D.; Keenan, T.F.; Migliavacca, M.; Ryu, Y.; Sonnentag, O.; Toomey, M. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agric. For. Meteorol.* **2013**, *169*, 156–173. [CrossRef]
43. Auld, T.D.; Bradstock, R.A. Soil temperatures after the passage of a fire: Do they influence the germination of buried seeds? *Austral. Ecol.* **1996**, *21*, 106–109. [CrossRef]
44. Oswald, B.P.; Wellner, K.; Boyce, R.; Neuenschwander, L.F. Germination and Initial Growth of Four Coniferous Species on Varied Duff Depths in Northern Idaho. *J. Sustain. For.* **1998**, *8*, 11–21. [CrossRef]
45. Johnstone, J.F.; Chapin, F.S. Effects of Soil Burn Severity on Post-Fire Tree Recruitment in Boreal Forest. *Ecosystems* **2006**, *9*, 14–31. [CrossRef]
46. Palmer, H.D.; Denham, A.J.; Ooi, M.K.J. Fire severity drives variation in post-fire recruitment and residual seed bank size of Acacia species. *Plant. Ecol.* **2018**, *219*, 527–537. [CrossRef]
47. Oakman, E.C.; Hagan, D.L.; Waldrop, T.A.; Barrett, K. Understory Vegetation Responses to 15 Years of Repeated Fuel Reduction Treatments in the Southern Appalachian Mountains, USA. *Forests* **2019**, *10*, 350. [CrossRef]
48. Waldrop, T.A.; Hagan, D.L.; Simon, D.M. Repeated Application of Fuel Reduction Treatments in the Southern Appalachian Mountains, USA: Implications for Achieving Management Goals. *Fire Ecol.* **2016**, *12*, 28–47. [CrossRef]