**Title Page**

Pitch Pine (*Pinus rigida*) Response to Fire Absence and Topographic Factors at Mt. Desert Island

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Key words

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**ABSTRACT**

Globally rare pitch pine (*Pinus rigida* Miller) is thought to depend on intermittent fire, which encourages reproduction and niche preservation. At Mt. Desert Island in Acadia National Park (ME, USA) a major, stand-replacing conflagration enveloped a portion of the island in 1947; since then there has been no recurrence of fire. Other populations have been unaffected by fire disturbance for over one hundred and twenty years. Despite the absence of fire, pitch pine persists at Mt. Desert Island, suggesting that other environmental drivers may be as or more important than fire in that system. We examined the influence of fire history and topography (i.e., elevation, aspect, and slope) on individual trees in four separate stands at Mt. Desert Island. Generally, topography was found to be a more important driver of leaf and plant level traits than fire history, with individuals possessing greater stress tolerance traits at high elevation. We attribute this to changes in topographical and soil characteristics along the gradient. These results challenge the suggestion that fire is the primary driver of pitch pine persistence at Mt. Desert Island and indicate that pitch pine has the capacity to thrive across a wider array of environments. These results can serve to better understand and manage this species in an ever-changing future world.

**INTRODUCTION**

On Mt. Desert Island at Acadia National Park in Maine USA, pitch pine (*Pinus rigida* Miller), the most northerly member of the southern yellow pines (Plain, Kuser and Ledig 1987), dwell at the edge of their northeastern range (Fig. 1) in heathland, pine barren communities. Over millennia, their persistence (ability to remain in a particular setting) is defined by frequent fire disturbance that regulates competition, removes post-fire pyrogenic carbon (C) from the soil and drives the radiation of fire adaptations. Among the most significant fire adapatations are serotinous cones (which typically open only when fire engulfs the tree), thickened bark to withstand scorching and epicormic sprouting along branches and trunk (Little 1953). These features were present on Mt. Desert in 1947 (Fig. 1) when an intense October fire started in a dump just west of Bar Harbor, on the east side of the island. Ferocious winds whipped the fire into a frenzy and, notwithstanding efforts to subdue it, persevered for nearly two weeks. Since that time, fire suppression has been used to avoid a repetition of the tragic consequences from that fire. Interestingly, in ensuing decades, tree pyrogenic adaptations have diminished, perhaps as the result of phenotypic plasticity, shifting away from cone serotiny (Conkey, Keifer and Lloyd 1994; Jordan, Patterson and Windisch 2003). As there is less pressure to produce seeds that survive in the midst of a fire (Givnish 1981), there may also be less need for thick bark or epicormic sprouting (Renninger *et al.* 2013). Past studies have speculated that tree defenses are shifting from fire resiliency to traits that may help deal with other abiotic conditions such as warmer temperatures and increasing summer drought (Day *et al.* 2005; .

Recent history of pitch pine population success in fire-suppressed locations such as Mt. Desert Island defies a theory that fire (natural or proscribed) is likely a requirement every six to twenty-five years for pine barren well-being (Jordan, Patterson and Windisch 2003). While fire responses have been studied previously (Foereid *et al.* 2015; Carlo *et al.* 2016; Neill *et al.* 2007), there is a critical need to understand other factors that might be influencing pithc pine persistence in the absence of fire at Mt. Desert Island.

Here, we address one such factor that has not yet been thoroughly assessed at Mt. Desert in comparison with fire history, topography (Parshall and Foster 2002; Fig. 2). Specifially, we use four populations that lie along a topographical and fire history gradient (Fig. S1) as proxies for more than a dozen other colonies, to examine the effects of elevation, aspect and slope (Bolstad and Stowe 1994) on soil (ecosystem), leaf, and plant-level traits. The four populations were chosen to represent a factorial combination of elevation (high or low) and fire history (having experienced the 1947 stand-clearing fire or not). First, we characterize differences in topographical features, including slope and aspect, given that these are likely important non-elevation topographical drivers of the traits examined. We then explore aspects of the soil environment, including soil carbon as well as macro and micro nutrient concentrations. Following previous studies, we expected to find less soil carbon (DeBano 1981), greater alkali cations (Kolden *et al.* 2017), and increased solubilized minerals (Caldwell and Richards 1989) in soils which experienced the 1947 fire. We also foresaw there would be greater soil carbon at low elevations due to thermal exfoliation (as explained by Shakesby and Doerr 2006) or a failure of fire to remove pyrogenic carbon (Doerr *et al.* 2018) in former fire zones. We also measured soil water retention, which we expected to be greater at sites that experienced the 1947 fire, as pyrogenic carbon is known to increase soil water retention (Licht and Smith, 2020). Beyond that, we anticipated higher soil water retention at low elevations due to flat terrain (alleviating erosion mechanics).

We hypothesized that topographical and fire history-driven changes to the growth environment would manifest in changes in leaf- and plant-level traits. We expected that stress induced by topographical features and low soil water retention at high elevation would lead to increased intrinsic water use efficiency (iWUE; Wang *et al.* 2017), as a stress tolerance response. We also hypothesized a reduction in leaf nutrients at high elevation, mimicking likely reductions in the soil. In addition, there was the prospect that fire history might alleviate these stress indicators, as a result of increased soil nutrients and water retention. At the plant level, we predicted plants would be smaller in heigh and DBH, have narrower canopy, and be more sparsely clustered (greater distance between conspecific neighbors) at high elevation, again as a result of the topography- and soil-induced stress. We expected to find smaller trees in areas that had experienced the 1947 fire due to age, but that the height difference would be less at high elevation due to stress-reducing effects of fire on the soil environment.

**METHODS**

**Study Extraction Sites**

We investigated fifteen pitch pine specimens at each of four sites at Mt. Desert Island (Fig. 2, Tab. 1), factorially crossed in a fire history (Miller *et al*. 2017) by elevation design: (1) Wonderland trail at an average of 58.5 ft elevation (low elevation, outside the footprint of the 1947 fire), (2) Gorham cliffs at an average of101.5 ft (low elevation, within the footprint), (3) St. Sauveur trail at an average of563.5 ft (high elevation, outside the footprint) and (4) South Cadillac trailat an average of 912 ft (high elevation within the footprint). Elevation differences were more stark at two trail transects St. Sauveur and South Cadillac trails. Soils at all four sites were overlain with rapidly drying needle duff, porous, and comprised of acidic hornblende granite or Ellsworth schist (Day *et al.* 2005). In addition they were uniformly shallow (varying between 0.7-2.5 cm), homogeneous, and low in fertility (Butak 2014). In some cases, sampling was limited by time, weather and site access yielding uneven sample accumulations. Our analytical methods were designed to deal with uneven sample sizes.

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**Soil Elements and Water Retention (SWR)**

Soils were excavated by hand trowel and soil probe (Accuproducts, Saline, MI, USA); soil C, N and C/N were calculated from elemental analysis. 70 mL soil samples were extracted at fifteen tree locations at four sites, from <10.5 cm (Oa-Ab) horizon above bedrock. In a laboratory 50 g H2O were added to each aliquot to assess net water retention as a subset of soil moisture evaporation (*ψ*g) to determine net evaporative loss or adsorption to surfaces. Soil water retention analysis was conducted according to the Fields method (Lichtand Smith 2018). Retention effects of gravitational and evaporation forces was made on a wet basis where Wm=g H2O **●** (g moist soil)-1 (Qi, Jingfang and Wenwei 2018). We also used a set of #10-#120 mesh sieves (Advantech, Wisconsin, USA) to determine presence of close-to-the-surface fine charcoal particulate matter symptomatic of recalcitrant pyrogenic material at all four sites.

**Leaf Traits**

Maximizing seasonal data relative to active growth during the driest months of the summer was achieved by obtaining C isotopic data (δ13C) and N isotopic data (δ15N) of fully expanded leaves (needle cluster) of 15 individuals at each site. Sample fascicles were separated and dried for two days at 60 ◦C ground in a SPEX ball mill (Metuchen, NJ, USA), weighed to +/- 2 mg for leaf tissue and +/- 5 mg for soil using a Cole-Palmer (Vernon Hills, IL, USA) micro analytic balance and rolled in Costech (Valencia, CA, USA) 5 x 9 mm tin capsules. A Thermo Delta (Waltham, MA, USA) V+ IR-MS continuous flow isotope ratio mass spectrometer with a universal triple collector was used. Combustion gasses were separated on a gas chromatograph column, passed through a diluter and reference gas box, and introduced into the spectrometer. δ13C was used to indicate water use efficiency (iWUEδ13C) (Farquhar et al. 1989). Leaf tissue was obtained from excision of basal fascicle bundles at 1.06 m. 50 mL samples of needles were separated, cut and dried for two days at 60 ◦C. Then they were ground in a SPEX ball mill (Metuchen, NJ, USA), sieved to <10 mm, and <2 mL were fed to a Leco CN-2000 Carbon-Nitrogen Analyzer (Leco Corp., St. Joseph, MI) coupled with the spectrometer to determine C and N concentrations. 35 mL aliquots were submitted for standard plant tissue nutrient analysis using a TJA Model 975 AtomComp ICP-AES (Thermo Jarrell-Ash Corp., Franklin, MA). The method comprised submersion in a 5 mL trace-metal-grade HNO3 treatment, then refluxed on hot block at 80 ◦C for two hours and diluted to 25 mL with 0.4 micron PTFE syringe filters to access extractable macro and micro inorganics.

**Plant-level Traits**

calibration between two ,, Mean distances between sampled trees were calculated including up to five of the nearest, reproductively mature conspecific (within 5 m) neighbors (Churchill *et al.* 2012)—this clustering method served as a surrogate, but inverse, measure for stand density (Mosseler, Rajora and Major 2004).

**Statistical Analysis**

All data were analyzed using a similar linear model structure with elevation as a continuous independent factor and presence of the 1947 fire (yes or no) as a categorical independent factor. The interaction between elevation and presence of the 1947 fire was also included as an independent factor in each model. In total, 27 models were fit with the following dependent variables: tree height (m), canopy spread (m), DBH (cm), mean distance between neighbors (m), foliar carbon (C, %), foliar nitrogen (N, %), foliar C/N (unitless), foliar δ13C (‰), foliar δ15N (‰), foliar calcium (Ca2+ %), foliar phosphorus (P, %), foliar potassium (K+, %), foliar magnesium (Mg2+, %), foliar aluminum (Al+, ppm), foliar zinc (Zn, ppm), soil C (%), soil N (%), soil C/N (unitless), soil Ca2+, P, Al+, Zn, and soil water retention (%). Tree height, canopy spread, DBH, foliar P, foliar K+, foliar Zn and soil C/N were log transformed to meet model assumptions of normality and heterogeneity of variances, while soil water retention was arcsin square root transformed to meet model assumptions. All linear models were fit using the ‘lm’ function in R (R Core Team 2019). Type II F-tests were used to determine the statistical significance of each factor in each model using the ‘Anova’ function in the ‘car’ package in R (Fox and Weisberg, 2019). Slopes and intercepts for plotting were determined using the ‘emmeans’ package in R (Lenth and Lenth 2018). Because aspect data is circular in nature, we analyzed aspect data using a Watson’s Two-Sample Test of Homogeneity as implemented in the R package ‘circular’ (Agostinelli and Lund 2017). Specifically, one-to-one comparisons were done between each site in all six possible combinations. All analyses were performed with R version 4.0.5 (R Core Team 2019).

**RESULTS**

*Topographical Features*Watson’s two sample t-tests indicated that the individual aspects of all sites differed with respect to one another except for the two sites that experienced the 1947 fire (Gorham cliffs and South Cadillac Trail), which had similar aspects (Fig. 3 and Tab. 2). There was an interaction between slope and fire history (*F*1,56 = 108.1, *P* < 0.05) that indicated that the slope was greater for individuals at the low elevation site that experienced the 1947 fire (Gorham cliffs) than low elevation individuals that did not experience the fire (Wonderland), with the reverse being true at high elevation (Table 1).

*Soil Elements and Water Retention*

Soil C concentrations were greater at lower elevations (*P* < 0.05), but were unaffected by fire history or their interaction (*P* > 0.05 in all cases, Fig. 4 and Tab. 3). Soil N and C/N did not vary with elevation, fire history, or their interaction (*P* > 0.05 in all cases, Fig. 4 and Tab. 3).

Soil Ca2+ decreased with elevation (*P* < 0.05, Fig. 5 and Tab. 4), regardless of fire history. Soil P, Mg2+, and Zn did not vary with elevation, fire history, or their interaction (Tab. 4). Fire accounted for a 48% reduction in K+ at fire-experienced sites (*P* < 0.05, Fig. 5 and Tab. 4), regardless of elevation. There was an interaction between fire history and elevation (*P* < 0.01, Tab. 4) that indicated that soil Al+ increased with elevation in sites that did not experience the 1947 fire and decreased with elevation at sites that did experience the 1947 fire (Fig. 5).

There was an interaction between elevation and fire history on soil water retention (SWR; *P* < 0.01, Fig. 4 and Tab. 3), driven by higher SWR at sites that experienced the 1947 fire at low elevation, an effect that was diminished at higher elevations (Fig. 4).

*Leaf Isotopes and Elements*

Trees at higher elevations experienced less negative δ13C (*P* < 0.01, Fig. 6 and Tab. 5), reflecting greater water use efficiency, regardless of fire history. There were no significant effect of fire history, elevation, or their interaction on δ15N (*P* > 0.05 in all cases, Fig. 6 and Tab. 5)*.*

Foliar C was greater in trees at sites that experienced the 1947 fire (*P* < 0.05, Fig. 6 and Tab. 5), regardless of elevation; however there was no effect of fire history, elevation, or their interaction on foliar N or C/N (P > 0.05 in all cases, Fig. 6 and Tab. 5).

Foliar Ca2+ was negatively impacted by increasing elevation (*P* < 0.001, Fig. 7 and Tab. 6), regardless of fire history. Our model indicated that foliar P was significantly higher at fire-involved sites (*P* < 0.01, Fig. 7 and Tab. 6), regardless of fire history. Foliar K+ was reduced by fire involvement at high elevations, but not low elevations (elevation x fire: *P* < 0.05, Fig. 8C and Tab. 6). Neither foliar Al+ nor Mg2+ differed by fire history, elevation, or their interaction (*P* > 0.05 in all cases; Fig. 7 and Tab. 6). Foliar Zn concentrations decreased with increasing elevation (*P* < 0.01, Fig. 7 and Tab. 6), regardless of fire history.

*Plant-level Traits*

There was a significant interaction between fire and elevation on tree height (*P* < 0.01, Tab. 7), which indicated that historical fire presence had a negative impact on tree height at high, but not low, elevation (Fig. 8). Increasing elevation reduced DBH (P < 0.001; Fig. 8 and Tab. 7), regardless of fire history. Canopy spread was reduced at high elevation (*P* < 0.01, Fig. 8 and Tab. 7), regardless of fire history. Distance between neighbors was greater at high elevation sites (*P* < 0.001, Fig. 8 and Tab. 7), regardless of fire history.

**DISCUSSION**

*Soil Characteristics*

Soil fertility and water retention varied across our environmental gradient. We were curious about the influence of subsurface charcoal as a soil component in fire-exposed areas. At nearby, burned-over Cadillac Brook (below the heights of South Cadillac trail) earlier paleo (Lafon *et al.* 2014) and fossil indicator reports (Patterson, Edwards and Maguire 1987; Verma and Jayakumar 2012) underscore the presence of charcoal. However, our shallow excavation and subsequent screening did not reveal noticeable charcoal particulate in sifted fines from samples at South Cadillac or Gorham cliffs, places where it was most expected, or at Wonderland and St. Sauveur, where it was not. There was subsequently no changes in soil C with fire history, although there was a reduction at higher elevations.

Patel *et al.* (2018) studied soil N in several watersheds (drainages) below South Cadillac trail, at low to mid-elevation, to determine recalcitrant atmospheric deposition since the 1947 fire. Since fire is known to increase N losses there was an expectation of lower nitrogen at sites closer to the most intense burns, but they found no evidence for this (Patel *et al.* 2018). These are consistent with our findings. Fire also did not significantly influence any of the other soil nutrients we measured, despite strong topographical differences.

A previous pine barren study reported that pyrolysis (either natural or anthropogenic) increased SWR (Licht and Smith 2020) and we found support for this at low elevations. Interestingly, this was despite greater slopes at the site that experienced fire at low elevation, which we would have expected to reduce SWR.

*Leaf Traits*

Intrinsic water use efficiency, indeed by δ13C, has been shown to increase in the presence of pyrolytic soil (Licht and Smith 2020). However, we found no effect of the 1947 fire on this trait. Instead, δ13C (and, thus water use efficiency) increased with elevation, supporting previous findings (Wang *et al.* 2017; Chen, Wang and Jia 2017, Körner *et al*., 1986; Friend *et al*., 1989; Bresson *et al*. 2009). At Mt. Desert, where elevation gradients are a significant feature of the landscape, this response is indicative of plant stress tolerance response (to higher wind turbulence, low pressure, and more quickly drying soils) as a feature of upper elevation life (Wang *et al.* 2017).

We expected that an increase in elevation would drive increases in leaf nutrients, particularly leaf N, to support high elevation photosynthesis at low stomatal conductance, as has been shown and is expected from physiological theory (Wang *et al.* 2017). This was not the case. A reduction in some soil nutrients (e.g., Ca2+) may have played a role in this (Firn *et al.* 2019), but may also have been the effect of non-measured variables, such as nutrient mineralization.

Despite a lack of soil nutrient responses, we found that fire involvement significant increased foliar P, possibly as the result of greater P availability. However, this was not consistent with our soil analysis. Further studies are needed to understand the connection between fire involvement, topography, soil nutrients, and foliar nutrients at Mt. Desert Island. A closer examination of fungal processes may yield more clear findings (Dove and Hart 2017).

*Plant-level Traits*

Elevation was the primary driver of plant traits, resulting in smaller, less clustered trees at hig versus low elevation. Interestingly, there was relatively little difference in these responses with fire involvement, which we expected to reduce clustering and tree size regardless of elevation due to effects on tree age. Although tree ages were unknown, we expected older individuals at sites that did not experience the 1947 fire. In fact, this lack of difference may be an indicator of stimulation of pitch pine growth after fire, for instance as a result of reduced competition (Jordan, Patterson and Windisch 2003). This might suggest that a shift back could further spur dispersal, but, despite a significant fuel buildup in the forests on the island, this would require a change in current management policies. Coupled with climate projections (Fernandez *et al.* 2015), we can predict potential ledge population enlargement is unlikely to occur as a function of anthropogenic intervention. Nonetheless, our findings in non-fire involved sites suggest that pitch pine can persist in the absence of fire. However, further studies are needed to examine how long this will last.

*Disturbance, Climate Factors and Predictions for Species Status*

Until now disturbances such as mechanical thinning and bioturbation (Abney *et al.* 2019), disease such as *Ploioderma lethale* (needle cast, Little and Garrett 1990), deer browsing and rodent damage (Ledig, Hom and Smouse 2013), and insect herbivory (Lesk *et al.* 2017) are not management factors at Mt. Desert Island as they are in barrens elsewhere. Yet, a possibly catastrophic problem may occur due to a combination of a prolonged fire interval and increases in annual winter temperatures (Lesk *et al.* 2017)—namely the potential invasion within the next decade of an herbivore, Southern pine beetle (*Dendroctonus frontalis* Zimmer or ‘SPB’). This herbivore has already paid a deadly visit to New Jersey and Long Island NY (Dodds *et al.* 2018). Unless its progress is deterred by predators like double checkered clerid (*Thanasimus dubius*; Coulson and Klepzig 2011), or some undetermined climate factor, pitch pines along with understory plants, butterflies and moth members of the Acadia ecosystem are vulnerable to predation (Lesk *et al.* 2017).

It is no doubt that a warming climate is having the greatest impact on island vegetative prospects including the fortunes of pitch pine. MprojectAccording to several studies (Day *et al*. 2005; Lee *et al*. 2019) warming climate impacts habitat suitability and pitch pine tendencies to consolidate, regenerate or migrate. What has been clear for almost three decades is the effect of global climate change on physiological traits. Day, Greenwood and White (2001) found an uptick in annual temperatures signaled increased leaf-air vapor pressure deficits that negatively impacted pitch pine stomatal conductance and limited gas exchange. In a related report, scientists found warming trends (Kunkel *et al* 2013) increased pitch pine reproductive difficulties (Ledig, Smouse and Hom 2015). These trends include weather-related effects such as episodic drought, harsh winds, and salt spray (Fernandez *et al.* 2015) as well as increased cold intolerance (Steiner and Berrang 1990). What is not clear istree will be shaped by a continuing rise in What appears to be more certain is the prediction (Day *et al.* 2005) that pitch pine colonies will suffer due to a combination of diminished open space capacity, loss of enriched substrates and elimination of suitable habitats. Our study indicates that pitch pine physiology may be more flexible than previously thought, as we find trait shifts and population persistence along a large topographical gradient. However, global changes are likely to present these population with novel conditions that may override this flexibility. Future monitoring, manipulative, and modling studies will be critical to ensure the future persistence of this important species.

## Data Availability Statement

Data used in this article can be found at the following repository: <https://github.com/SmithEcophysLab/mtDesertIsland_Pinusrigida> (DOI:10.5281/zenodo.4663255).

## Author Contributions

JL and NGS conceived the work. JL, RM, and NGS contributed substantially to the interpretation of the data and to drafting the manuscript, gave final approval of the version submitted, and agreed to be accountable for all aspects of the work. Questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. JL carried out sample collection and field measurements, conducted soil water retention tests and prepared samples for EA-IRMS analysis. NS performed C/N foliar analysis. NGS and RM conducted statistical analyses and formulated figures and tables.

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