**Title Page**

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

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KEYWORDS

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**ABSTRACT**

Pitch pine (*Pinus rigida*) is a foundational species at Mt. Desert Island in Acadia National Park (ME, USA), at its Northeast limit. It is thought to depend on intermittent fire every five to twenty-five years which encourages reproduction and niche preservation. Yet this is not the case; it has been almost seventy-five years since a stand-replacing conflagration occurred on the eastern side of the island and one hundred years for trees on the western side. Given this extended fire absence we speculate as to persistence shown by pitch pine especially in light of new climate pressures and determine if other factors such as topography may be driving tenacity in that system. We characterized the influence of fire history and topography on sixty individual trees using systematic and cluster sampling methods with non-fixed intervals between trees (1m to 4m) and non-fixed directionality (employing nine compass points). Trees were selected based on their fire history (experience or no experience with the 1947 fire) in four separate stands divided between west and east sides of the island at low and high elevation gradients. We found topography (varying between flat, ledge and cliff) was 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 response 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 and suggests trees thrive across a wide array of environments, which may be made more problematic by increased summer and winter warmth coupled with heightened moisture. Our results may be applied to the study of other pitch pine populations where fire is absent and where flat, ledge and cliff topography affect pitch pine persistence.

**INTRODUCTION**

On Mt. Desert Island at Acadia National Park in Maine USA, imperiled (S2) pitch pine (*Pinus rigida* Miller), a member of the southern yellow pines (Plain *et al*. 1987), dwell at the edge of their northeastern range (Figure 1). Over millennia, pitch pine 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. Recent history of pitch pine population success in fire-suppressed locations at Mt. Desert Island defies a theory that (natural or prescribed) fire is likely a requirement every six to twenty-five years for pine barren well-being (Jordan *et al*. 2003). In fact the most recent fire event at Mt. Desert occurred seventy-four years ago when an intense October fire burned for nearly two weeks (Figure 1; Pyne 2019). Since that time, fire suppression has been employed to avoid a repetition of the consequences from that event. Long-lived adaptations to fire occurrence (Givnish 1981), there as elsewhere, include serotinous cones (Conkey *et al*. 1995; Jordan *et al*. 2003; Ledig Smouse and Hom 2015), thickened bark to withstand scorching (Little and Garrett 1990) and epicormic sprouting along branches (Renninger *et al.* 2013). Past studies have observed physiological changes in pitch pine over the past thirty years (Day *et al.* 2001). More specifically, there is speculation that these shifts are modifying tree defenses from fire resiliency and fire dependence to adaptation to new abiotic conditions such as warmer temperatures and increasing summer drought (Day *et al.* 2005; Buma *et al.* 2013). As a further sign of a transition from a pyrolytic past and fire dependency, pitch pine increasingly anchor desertified communities of understory flora not necessarily associated with fire adaptation including *Sibbaldiopsis tridentata*, *Empetrum nigrum*, *Kalmia angustifolia*, *Hypercium perforatum* and *Campanula rotundifolia*.

Responses to natural and anthropogenic fires are described frequently (Neill *et al.* 2007; Foereid *et al.* 2015; Carlo *et al.* 2016) in forests to the south of Mt. Desert Island; as they do not occur on the island, it is critical to understand other factors that might be influencing pitch pine persistence. We address one such factor, topography, not as yet assessed at Mt. Desert Island in comparison with fire history (Parshall and Foster 2002; Figure 2). Specifically, we study four populations that lie along a graduated topographical and fire history gradient (Figure 2) as proxies for more than a dozen other colonies, to examine the effects of elevation, aspect and slope (Bolstad and Stowe 1994) on soil, leaf, and plant-level traits. Individual trees were chosen to represent a factorial combination of elevation (high or low) and fire history (having experienced the 1947 stand-clearing fire or not) and were characterized in several ways. First, we examine topographical data from elevation. Next we assess slope and aspect measurements (at flat, cliff and ledge communities), given that these are likely important non-elevation topographical drivers of the traits examined (Howard and Stelacio 2011; Hanson 2017; Nowacki and Abrams 2008). Then we 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 1998), greater alkali cations (Certini 2005) and increased solubilized minerals (Caldwell and Richards 1989) in soils which experienced the 1947 fire. We predicted that 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 in former fire zones (Doerr *et al.* 2018). We also measured soil water retention, which we speculated would be greater in stands 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 theorized a reduction in leaf nutrients at high elevation, mimicking likely similar 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 height and stem diameter of the bole at breast height (DBH), and have narrower canopy~~, and be more sparsely clustered (greater distance between conspecific neighbors)~~ at high elevation, as a result of ~~the~~ topography- and soil-induced stress.

**METHODS AND MATERIALS**

*Study sites*

We investigated fifteen individual trees within each of four groups (*n*=60) at Mt. Desert Island (Figure 2, Table 1~~, Table S1~~). They were studied as independent replicates, using a combination of systematic and cluster sampling methods with non-fixed intervals between trees (1m to 4m) and non-fixed directionality (employing nine compass points). The four populations of trees were factorially crossed in a fire history (Miller *et al*. 2017) by elevation design. Topography comprises flat, cliff and ledge systems (Figure S1) spanning a 400 m elevation gradient: (1) Wonderland trail at an average of 17.57 m elevation (low elevation, outside the footprint of the 1947 fire), (2) Gorham cliffs at an average of33.17 m (low elevation, within the footprint), (3) St. Sauveur trail at an average of196.43 m (high elevation, outside the footprint) and (4) South Cadillac trailat an average of 306.16 m (high elevation within the footprint). We found a funnel-like effect at St. Sauveur and South Cadillac trail transects where larger clusters of pitch pine at lower elevation on those mountains gave way rapidly to much smaller groupings at higher elevation. While no coring was used to determine a dendrological metric for each cohort, we noted similarities between trees in fire-present precincts (Gorham Cliffs and South Cadillac Trail) according to features like height and stem diameter of the bole at breast height (DBH), which underscored assumptions about similar ages amongst the post-fire samples in each locale.

*Data Collection*

Single-point-in-time leaf and soil data were captured from 15 individuals per site for each of the four sites in the month of July in 2019 (10 individuals per site) and 2020 (5 individuals per site). Soils extracted proximate to trees in all four groups 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). ~~Leaf samples were derived from trees. In some cases, sampling was limited by time, weather and site access yielding uneven sample accumulations (see sample size for each measured variable in Table S1). Our analytical methods were designed to deal with uneven sample sizes (see Statistical Analysis section below).~~

*Topographic features*

A Kodak Trimble Juno 3B was used to obtain horizontal resolution of data plotted using between five and seven satellite telecommunication vehicles to maintain a maximum Position Dilution of Precision. These data were differentially corrected and have estimated accuracies in the horizontal and vertical direction of 2m, while selective availability was set to zero. Multiple satellite-configured GPS data (USGS 2m LIDAR 2010) determined coordinates for individual trees (Lubinski *et al*. 2003) as well as slope and aspect attributes using ArcGIS (version 10). Mapping of this type of data has been used in the past to compare physiography and recalcitrant chemical biogeography, particularly in fire prone contexts (Kolden and Weisberg 2007; Szpakowski and Jensen 2019).

*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 obtained at a depth <10.5 cm in an (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 *et al.* 2018). We also used a set of #10-#140 mesh sieves (Advantech, Wisconsin, USA) to determine presence of close-to-the-surface fine charcoal particulate matter symptomatic of recalcitrant pyrogenic material.

*Leaf Traits*

We obtained C, N, C/N, C isotopic data (δ13C) and N isotopic data (δ15N) of fully expanded leaves (needle cluster) of 15 individual trees in each group. For four individuals, machine error caused erroneous leaf N values (N > 15%). These were omitted from the analysis. All individuals selected had stem DBH greater than 13 cm. Sample fascicles (one per tree) 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*

We measured individual tree height, DBH, canopy spread and distance between conspecific neighbors. Tree height was estimated using a plastic clinometer (Kager, Lunenberg, MA USA) and 30 m tape. DBH was measured at 1.06 m above the ground using an expandable cloth measuring tape. Canopy spread across the first nodal branch expanse below the crown was measured using calibration between two aluminum flags as a ground truth reference. We measured from the first nodal branch expanse because crown shapes were relatively consistent between trees at the first node. ~~Mean distances between sampled trees were calculated including up to five of the nearest, reproductively mature conspecific (within 5 m) neighbors (Churchill~~ *~~et al.~~* ~~2013)—this clustering method served as a surrogate, but inverse, measure for stand density (Mosseler~~ *~~et al~~*~~. 2004).~~

*Statistical Analysis*

All data were analyzed using a similar linear model structure with elevation as a continuous independent factor (i.e., a covariate) and presence of the 1947 fire (yes or no) as a categorical independent factor (i.e., grouping factor). The interaction between elevation and presence of the 1947 fire was also included as an independent factor in each model. Mathematically, this can be shown as:

Y = β0 + β1(elevation) + β2(fire history) + β3(elevation\*fire history) + ε (Eqn. 1)

where Y is the response variable, β0 is the model intercept, β1 is the slope of the effect of elevation (a continuous variable or covariate), β2 is the slope of the effect of fire history (a categorical or grouping variable with two levels), β3 is the slope of the interaction between elevation and fire history, and ε is an error term. In total, 25 models were fit with the following dependent variables: tree height (cm), canopy spread (cm), DBH (cm), ~~mean distance between neighbors (m),~~ foliar carbon (C, %), foliar nitrogen (N, %), foliar C/N (unitless), foliar δ13C (‰), foliar δ15N (‰), foliar aluminum (Al+, mg kg-1), foliar calcium (Ca2+; mg kg-1), foliar magnesium (Mg2+; mg kg-1), foliar phosphorus (P; mg kg-1), foliar potassium (K+; mg kg-1), foliar zinc (Zn; mg kg-1), soil C (%), soil N (%), soil C/N (unitless), soil Al+ (mg kg-1), soil Ca2+ (mg kg-1), soil Mg2+ (mg kg-1), soil P (mg kg-1), soil K+ (mg kg-1), soil Zn (mg kg-1), and soil water retention (mg kg-1). 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). Type II tests are robust to unbalanced designs (Langsrud 2003~~; Table S1~~). 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 trees differed with respect to one another except in two groups which had similar aspects (Figure 3 and Table 2) and experienced the 1947 fire (Gorham cliffs and South Cadillac Trail). 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 low elevation that experienced the 1947 fire (Gorham cliffs) than low elevation individuals (Wonderland) that did not. The reverse was true at high elevation (Table 1).

*Soil elements and water retention*

Soil C concentrations decreased as elevation increased (*P* < 0.05), but were unaffected by fire history or their interaction (*P* > 0.05 in all cases, Figure 4 and Table 3). Soil N and C/N did not vary with elevation, fire history, or their interaction (*P* > 0.05 in all cases, Figure 4 and Table 3).

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

There was an interaction between fire history and elevation (*P* < 0.01, Table 4) where soil Al+ increased at elevated tree locations that did not experience the 1947 fire and decreased at lower level trees which did experience that event (Figure 5). Soil Ca2+ decreased with elevation (*P* < 0.05, Figure 5 and Table 4), regardless of fire history. Fire accounted for a 48% reduction in K+ at fire-experienced locations (*P* < 0.05, Figure 5 and Table 4), regardless of elevation. Soil P, Mg2+, and Zn did not vary with elevation, fire history, or their interaction (Table 4).

*Leaf isotopes and elements*

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

Foliar C was greater in trees that experienced the 1947 fire (*P* < 0.05, Figure 6 and Table 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, Figure 6 and Table 5).

Foliar Ca2+ was negatively correlated with elevation (*P* < 0.001, Figure 7 and Table 6), regardless of fire history. Our model indicated that foliar P was significantly higher in 1947 fire-involved trees (*P* < 0.01, Figure 7 and Table 6), regardless of fire history. Foliar K+ was lower at fire involved high elevations, but not at a low elevation like Wonderland (elevation x fire: *P* < 0.05, Figure 7 and Table 6). Neither foliar Al+ nor Mg2+ differed by fire history, elevation, or their interaction (*P* > 0.05 in all cases; Figure 7 and Table 6). Foliar Zn concentrations decreased with increasing elevation (*P* < 0.01, Figure 7 and Table 6), regardless of fire history.

*Plant-level traits*

There was a significant interaction between fire and elevation on tree height (*P* < 0.01, Table 7) and DBH (*P* < 0.05, Table 7). These effects indicated that the smallest trees were found at the high elevation site that experienced fire (SCT; Figure 7). Canopy spread was negatively correlated with elevation (*P* < 0.01, Figure 8 and Table 7), regardless of fire history. ~~Distance between neighbors was greater at high elevation locations (~~*~~P~~* ~~< 0.001, Figure 8 and Table 7), regardless of fire history.~~

**D****ISCUSSION**

*Soil characteristics*

Soil fertility and water retention varied across our ~400 m elevation 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 *et al.* 1987; Verma and Jayakumar 2012) underscore the presence of charcoal. In our exploration for charcoal remnants, we found a small amount (<2mL) of charcoal fines (passing through .25 mm sieve) across South Cadillac trail and fewer or none where other study trees were located. This may explain the lack of significant changes in soil C accounted for by fire history. However, there was a reduction in soil C with increasing elevation (Wonderland: 28.13%; South Cadillac Trail: 11.42%) and greater availability where older and more numerous trees were found. The reduction in soil C ~~also~~ coincided with a reduction in soil Ca2+ and, at fire exposed sites, soil Al+ at high elevations. Further studies that track environmental variables across the elevational gradient at Mt. Desert Island ~~would~~ should include other tree communities (e.g., Norumbega mountain (unburned) and Champlain mountain (burned) in 1947) useful to understanding the mechanisms driving this variation.

Patel *et al.* (2019) 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 we expected, like Patel *et al.* to find lower soil N where the most intense burns occurred, but this was not the case. 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 fire-exposed elevations at Mt. Desert at Gorham Cliffs where trees sat on steeper slopes than elsewhere. Pitch pine is known to be competitive in poor soils (Copenheaver *et al.* 2000); we were unable to clearly tease out the role of soil fertility in driving pine persistence. Yet the relative lack of soil response to fire history, *per se*, is perhaps a further indicator that soil fertility may play a more significant role in driving pitch pine persistence at Mt. Desert Island in locales which combine flat and fire absent characteristics. Further measurement may yield a clearer determination.

*Leaf traits*

Intrinsic water use efficiency, indicated by δ13C, has been shown to increase in the presence of pyrolytic soil (Licht and Smith 2020). We expected there might exist recalcitrant C in post-fire soils associated with study trees on South Cadillac and Gorham Cliff trails. However, we did not find this to be the case. Still, δ13C (and, thus water use efficiency) increased with elevation, supported by previous findings (Wang *et al.* 2017; Chen *et al*. 2017; Friend *et al.* 1989). At Mt. Desert, where elevation gradients are a significant feature of the landscape, this response is indicative of a 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 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.

We found that fire involvement significantly increased foliar P, possibly as the result of greater soil P availability; 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 (such as those conducted by Luo *et al*. 2017 following prescribed burns in New Jersey) may yield clearer findings (Dove and Hart 2017) to understand the influence of mycorrhizae on pitch pine in disjunct fire-present populations.

*Plant-level traits*

Elevation was the primary driver of plant traits, resulting in smaller~~, less clustered~~ trees at high versus low elevation. Likewise, we speculated traits like tree size and tree age were affected more by topography than fire history. Tree cores, taken at Wonderland by others (Patterson *et al.* 2016) dating to at least 1920 and even older trees dating back to 1880, at fire-absent Norumbega Mountain (Foard *et al*. 2015) reinforce that supposition. When comparing two non-1947 fire groups, St. Sauveur trail trees tended to be younger, on average, than their Wonderland counterparts; perhaps topography played a role in this but further investigation is required to reinforce that impression. As evidence of post-fire effects, larger trees at Gorham Cliffs may be an indicator of stimulation of pitch pine growth after fire, for instance as a result of initial, reduced competition (Jordan *et al.* 2003). If there were a shift back to fire in the future, based on increasing fuel buildup in the forests, the current equilibrium in pitch pine distribution would be likely to change. However, past studies indicate that recent climate projections (Fernandez *et al.* 2015) are a greater concern than fire (which would surely be suppressed quickly). We stipulate ledge and cliff population expansion, for example, is less likely to occur as a function of post-fire reproduction and more likely to occur where evergreen competitors are unable to compete in a ‘new’ environment. While our findings underscore pitch pine persistence in the absence of fire, further studies are needed to determine more precisely whether current extended fire intervals are likely to continue and to what extent absence accelerates persistence.

*Disturbance, climate factors and predictions for species status*

Until now, disease (such as *Lophodermium seditiosum* Minter Staley and Millar (needle cast), damage from deer browsing and rodents (Ledig *et al.* 2013) or insect herbivory from pests like black terpentine beetle (*Dendroctonus terebrans* Olivier) have not impacted Mt. Desert Island as elsewhere (e.g., Myles Standish Forest in Plymouth, MA). Yet, a different and more virulent herbivore problem is quite likely to present itself in the future due to a combination of a prolonged fire interval and increases in annual winter temperatures (Lesk *et al.* 2017)—namely Southern pine beetle (*Dendroctonus frontalis* or ‘SPB’). It has already induced substantial mortality in 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 a sudden turn towards cooler winter temperatures, pitch pine, along with understory plants, butterflies and moth members of the Acadia ecosystem, are vulnerable to SPB predation (Lesk *et al.* 2017).

No doubt a warming climate at MDI is having the greatest impact on island vegetative prospects, including the fortunes of pitch pine. Models project a negative impact on future vegetative status at Mt. Desert Island (Fernandez *et al.* 2015; Swanston *et al*. 2018). According 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. For almost three decades there appears to be a slight but ongoing effect of global climate change on physiological traits (Fernandez *et al.* 2015). Day *et al*. (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 *et al*. 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 unclear is the extent to which tree plasticity (Day Zazzaro and Perkins 2014) will be shaped by a continuing rise in temperatures and summer moisture. What appears to be more certain is the prediction that pitch pine colonies will suffer due to a combination of diminished open space capacity, loss of enriched substrates and elimination of suitable habitats (Day *et al.* 2005). 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 populations with novel conditions that may override this flexibility. Further monitoring, manipulative, and modeling studies will be critical to ensure the future persistence of this important species. Several other communities, for which this study served as a surrogate, would benefit from an even deeper analysis of stand density including measurement of stand basal area. Finally, the use of our data by conservation managers offers a better purchase on pitch pine persistence where fire is absent and where flat, ledge or cliff topography is present.

CONCLUSIONS

Aspect and slope accounted for differences in adaptivity (growth, expansion into greater stand density) often according to flatter terrain. Fire history at Gorham Cliffs generated greater impact than at South Cadillac trail. Though we conjectured fire history within a seventy-four year time frame would be more impactful (recency effect) on biological outcomes, across multiple gradients, than a longer interval of one hundred years, we did not find evidence to support that premise. However, there was a significant connection between fire history and SWR at lower elevations, irrespective of differences in slope. Flat and ledge pitch pine populations exhibited greater buoyancy than trees in more strenuous cliff situations according to our stand density findings. One indicator, intrinsic water use efficiency (δ13C), underscored a selective preference for either growth at low elevations or stress tolerance at high elevations as an example of multiple plant and ecosystem adaptations. We noted persistent colonization at flat and ledge locales which is likely an adaptive response in the face of increasing pressure from uneven moisture patterns and winter warming. At the same time we conjecture a continuing gap in fire return intervals is consistent with an expectation that fire absence is less consequential to pitch pine persistence than soil fertility and topography during this phase of the Anthropocene age (Crutzen and Stoermer 2000). These results challenge the suggestion that fire is the primary driver of pitch pine persistence and suggests trees thrive across a wide array of topography and environments made more problematic by increased summer and winter warmth coupled with heightened moisture.

**Table 1** Mean topographic features for individuals at each site.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Site** | **1947 Fire** | **Type** | **Latitude (°)** | **Longitude (°)** | **Elevation (m)** | **Slope (°)** | **Aspect (°)** | **Compass** |
| Gorham Cliffs | Yes | Cliff | 44.328 | -68.185 | 33.2 | 31.9 | 151.5 | SE |
| South Cadillac | Yes | Ledge | 44.333 | -68.224 | 306.2 | 9.4 | 138.1 | SE |
| St. Sauveur | No | Cliff/Ledge | 44.311 | -68.326 | 196.4 | 13.3 | 262.6 | W |
| Wonderland | No | Flat/Hilly | 44.237 | -68.316 | 17.6 | 3.7 | 208.1 | S |

**Table 2** Watson’s Two Sample Test of Homogeneity results for aspect at each site.\*

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Gorham Cliffs** | **St. Sauveur** | **South Cadillac** |
| **Wonderland** | t = 0.259 \* | t = 0.288 \*\* | t = 0.194 \* |
| **Gorham cliffs** |  | t = 0.385 \*\* | t = 0.166 *ns* |
| **St. Sauveur** |  |  | t = 0.519 \*\*\* |

\*Key: t = test statistic, *ns* =not significant, \* = P < 0.05, \*\* = P < 0.01, \*\*\* = P < 0.001, P = P-value.

**Table 3** Analysis of variance results for the linear models with soil carbon (C), nitrogen (N), and C/N, and soil water retention (SWR).\*

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Soil C** | | | **Soil N** | | | **Soil C/N** | | | **SWR** | | |
|  | **df** | **F** | **P** | **df** | **F** | **P** | **df** | **F** | **P** | **df** | **F** | **P** |
| Elevation | 1 | 4.675 | **0.040** | 1 | 0.190 | 0.667 | 1 | 3.853 | *0.062* | 1 | 2.503 | 0.122 |
| Fire | 1 | 2.718 | 0.111 | 1 | 0.260 | 0.615 | 1 | 1.493 | 0.235 | 1 | 12.400 | **0.001** |
| Elevation x Fire | 1 | 0.404 | 0.530 | 1 | 1.153 | 0.295 | 1 | 2.771 | 0.110 | 1 | 12.981 | **0.001** |
| *Residuals* | *27* |  |  | *22* |  |  | *22* |  |  | *36* |  |  |

\* P-values < 0.05 are bolded. ~~Sample sizes for each variable can be found in Table S1.~~ Elevation in the model was a continuous variable (i.e., covariate) and fire was a categorical variable (i.e., grouping variable) with two levels (exposure to 1947 fire and no exposure to 1947 fire). Key: df = degrees of freedom, F = F-value, P = P-value.

**Table 4** Analysis of variance results for the linear models with soil aluminum (Al+), calcium (Ca2+), potassium (K+), magnesium (Mg2+), phosphorus (P), and zinc (Zn).\*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Soil Al+** | | **Soil Ca2+** | | **Soil K+** | | **Soil Mg2+** | | **Soil P** | | **Soil Zn** | |
|  | **df** | **F** | **P** | **F** | **P** | **F** | **P** | **F** | **P** | **F** | **P** | **F** | **P** |
| Elevation | 1 | 1.342 | 0.257 | 6.729 | **0.015** | 2.284 | 0.142 | 2.525 | 0.124 | 2.829 | 0.104 | 2.079 | 0.161 |
| Fire | 1 | 0.032 | 0.860 | 0.041 | 0.840 | 6.664 | **0.016** | 0.254 | 0.618 | 1.015 | 0.323 | 0.082 | 0.776 |
| Elevation x Fire | 1 | 7.851 | **0.009** | 0.135 | 0.716 | 0.100 | 0.755 | 0.224 | 0.640 | 0.065 | 0.801 | 2.883 | 0.101 |
| *Residuals* | *27* |  |  |  |  |  |  |  |  |  |  |  |  |

\* P-values < 0.05 are bolded and < 0.1 are italicized. ~~Sample sizes for each variable can be found in Table S1.~~ Elevation in the model was a continuous variable (i.e., covariate) and fire was a categorical variable (i.e., grouping variable) with two levels (exposure to 1947 fire and no exposure to 1947 fire). Key: df = degrees of freedom, F = F-value, P = P-value.

**Table 5** Analysis of variance results for the linear models with foliar δ13C and δ15N, carbon (C), nitrogen (N), and C/N.\*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **δ13C** | | | **δ15N** | | | **Foliar C** | | | **Foliar N** | | | **Foliar C/N** | | |
|  | **df** | F | **P** | **df** | **F** | **P** | **df** | **F** | **P** | **df** | **F** | **P** | **df** | **F** | **P** |
| Elevation | 1 | 6.870 | **0.011** | 1 | 3.382 | *0.071* | 1 | 0.227 | 0.636 | 1 | 3.930 | *0.053* | 1 | 3.985 | *0.051* |
| Fire | 1 | 2.336 | 0.132 | 1 | 3.754 | *0.058* | 1 | 4.388 | **0.041** | 1 | 1.711 | 0.197 | 1 | 0.205 | 0.653 |
| Elevation x Fire | 1 | 0.128 | 0.722 | 1 | 0.625 | 0.433 | 1 | 0.006 | 0.939 | 1 | 0.114 | 0.737 | 1 | 0.711 | 0.403 |
| *Residuals* | 56 |  |  | 56 |  |  | 56 |  |  | 52 |  |  | 52 |  |  |

\* P-values < 0.05 are bolded and < 0.1 are italicized. ~~Sample sizes for each variable can be found in Table S1.~~ Elevation in the model was a continuous variable (i.e., covariate) and fire was a categorical variable (i.e., grouping variable) with two levels (exposure to 1947 fire and no exposure to 1947 fire). Key: df = degrees of freedom, F = F-value, P = P-value.

**Table 6** Analysis of variance results for the linear models with foliar aluminum (Al+), calcium (Ca2+), potassium (K+), magnesium (Mg2+), phosphorus (P), and zinc (Zn).\*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Foliar Al+** | | **Foliar Ca2+** | | **Foliar K+** | | **Foliar Mg2+** | | **Foliar P** | | **Foliar Zn** | |
|  | **df** | **F** | **P** | **F** | **P** | **F** | **P** | **F** | **P** | **F** | **P** | **F** | **P** |
| Elevation | 1 | 0.341 | 0.563 | 13.302 | **0.001** | 3.158 | *0.084* | 2.557 | 0.119 | 0.012 | 0.914 | 8.007 | **0.008** |
| Fire | 1 | 0.021 | 0.887 | 0.843 | 0.365 | 4.071 | *0.051* | 0.507 | 0.481 | 8.309 | **0.007** | 0.050 | 0.824 |
| Elevation x Fire | 1 | 0.187 | 0.668 | 0.088 | 0.769 | 4.863 | 0.034 | 0.377 | 0.543 | 0.407 | 0.527 | 1.458 | 0.235 |
| *Residuals* | *36* |  |  |  |  |  |  |  |  |  |  |  |  |

\* P-values < 0.05 are bolded and < 0.1 are italicized. ~~Sample sizes for each variable can be found in Table S1.~~ Elevation in the model was a continuous variable (i.e., covariate) and fire was a categorical variable (i.e., grouping variable) with two levels (exposure to 1947 fire and no exposure to 1947 fire). Key: df = degrees of freedom, F = F-value, P = P-value.

**Table 7** Analysis of variance results for the linear models with slope, tree height, canopy spread, diameter at breast height (DBH), and distance between neighbors.\*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Canopy Spread** | | | **DBH** | | | | **Distance Between Neighbors** | | | | **Tree Height** | | | | |
|  | **df** | **F** | **P** | | **df** | **F** | **P** | | **df** | **F** | **P** | | **df** | **F** | **P** |
| Elevation | 1 | 12.657 | **0.001** | | 1 | 19.035 | **<0.001** | | 1 | 10.048 | **0.002** | | 1 | 13.115 | **0.001** |
| Fire | 1 | 0.006 | 0.937 | | 1 | 0.560 | 0.458 | | 1 | 0.155 | 0.696 | | 1 | 0.296 | 0.589 |
| Elevation x Fire | 1 | 1.890 | 0.175 | | 1 | 5.774 | **0.020** | | 1 | 0.969 | 0.329 | | 1 | 14.878 | **<0.001** |
| *Residuals* | 56 |  |  | | 56 |  |  | | 56 |  |  | | 56 |  |  |

\* P-values < 0.05 are bolded and < 0.1 are italicized. ~~Sample sizes for each variable can be found in Table S1.~~ Elevation in the model was a continuous variable (i.e., covariate) and fire was a categorical variable (i.e., grouping variable) with two levels (exposure to 1947 fire and no exposure to 1947 fire). Key: df = degrees of freedom, F = F-value, P = P-value, DBH = diameter at breast height.

## Figure legends

**Figure 1** Location of pitch pine populations on Mt. Desert Island used in this study. “H” and “L” indicate high and low elevation populations, respectively, within (orange) and outside (green) the 1947 fire extent. More information about the populations can be found in Table 1.

**Figure 2** Topographical maps showing the location of pitch pine individuals (blue dots) within each studied population on Mt. Desert Island. Areas in orange represent areas exposed to the 1947 fire.

**Figure 3** Relationship between elevation and soil carbon (A; black line: y = 24.40 - 0.046x), soil nitrogen (B), soil carbon/nitrogen (C) and soil water retention (D; red line: y = sin(0.69 – 0.0006x)^2 \* 100, blue line: : y = sin(0.47 + 0.0004x)^2 \* 100). Color of points and trendlines indicates the fire history with red and blue indicating exposure and no exposure to the 1947 fire, respectively. The trendlines indicate the modeled responses from the linear regression models. Only significant (*P* < 0.05 trends are shown). Black lines indicate relationships that are similar across fire history groups and blue and red lines indicate a difference in trends between fire history groups. Stars, triangles, diamonds, and squares correspond to measurements at Gorham Cliffs (GOR), South Cadillac (SCT), St. Sauveur (STS), and Wonderland (WON), respectively (Table 1).

**Figure 4** Relationship between elevation and soil aluminum (A; red line: y = exp(5.21 – 0.003x), blue line: y = exp(4.49 + 0.003x)), calcium (B; black line: y = 785.2 - 2.02x), potassium (C), magnesium (D), phosphorus (E), and zinc (F). Color of points and trendlines indicates the fire history with red and blue indicating exposure and no exposure to the 1947 fire, respectively. The trendlines indicate the modeled responses from the linear regression models. Only significant (*P* < 0.05 trends are shown. Black lines indicate relationships that are similar across fire history groups and blue and red lines indicate a difference in trends between fire history groups. Stars, triangles, diamonds, and squares correspond to measurements at Gorham Cliffs (GOR), South Cadillac (SCT), St. Sauveur (STS), and Wonderland (WON), respectively (Table 1).

**Figure 5** Relationship between elevation and δ13C (A; black line: y = -29.2 + 0.005x) and δ15N (B), foliar carbon (C), foliar nitrogen (D), and foliar carbon/nitrogen (E). Color of points and trendlines indicates the fire history with red and blue indicating exposure and no exposure to the 1947 fire, respectively. The trendlines indicate the modeled responses from the linear regression models. Only significant (*P* < 0.05 trends are shown. Black lines indicate relationships that are similar across fire history groups and blue and red lines indicate a difference in trends between fire history groups. Stars, triangles, diamonds, and squares correspond to measurements at Gorham Cliffs (GOR), South Cadillac (SCT), St. Sauveur (STS), and Wonderland (WON), respectively (Table 1).

**Figure 6** Relationship between elevation and foliar aluminum (A), calcium (B; black line: y = 1822.8 – 4.23x), potassium (C), magnesium (D), phosphorus (E), and zinc (F; black line: y = 3.72 – 0.0016x). Color of points and trendlines indicates the fire history with red and blue indicating exposure and no exposure to the 1947 fire, respectively. The trendlines indicate the modeled responses from the linear regression models. Only significant (*P* < 0.05 trends are shown. Black lines indicate relationships that are similar across fire history groups and blue and red lines indicate a difference in trends between fire history groups. Stars, triangles, diamonds, and squares correspond to measurements at Gorham Cliffs (GOR), South Cadillac (SCT), St. Sauveur (STS), and Wonderland (WON), respectively (Table 1).

**Figure 7** Relationship between elevation and canopy spread (A; black line: y = 5.95 – 0.0016x), diameter at breast height (DBH; B; red line: y = exp(3.33 – 0.0028x), blue line: y = exp(3.10 – 0.00024x)), ~~distance between neighbors (C; black line: y = 2.93 + 0.0035x),~~ and tree height (D; red line: y = exp(6.34 – 0.0027x), blue line: y = exp(5.93 + 0.0012x)). Color of points and trendlines indicates the fire history with red and blue indicating exposure and no exposure to the 1947 fire, respectively. The trendlines indicate the modeled responses from the linear regression models. Only significant (*P* < 0.05 trends are shown. Black lines indicate relationships that are similar across fire history groups and blue and red lines indicate a difference in trends between fire history groups. Stars, triangles, diamonds, and squares correspond to measurements at Gorham Cliffs (GOR), South Cadillac (SCT), St. Sauveur (STS), and Wonderland (WON), respectively (Table 1).

## Data availability statement

Data and analysis scripts used in this article can be found at the following repository: <https://github.com/SmithEcophysLab/mtDesertIsland_Pinusrigida> (DOI: 10.5281/zenodo.5708467).

## 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. NGS performed C/N foliar analysis. NGS and RM conducted statistical analyses and formulated figures and tables.

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