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Forest Management in a Changing Climate: Integrating Social and Biopysical Sciences to Inform Adaptive Responses to Future Uncertainty

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FOREST MANAGEMENT IN A CHANGING CLIMATE: INTEGRATING SOCIAL AND BIOPHYSICAL SCIENCES TO INFORM ADAPTIVE RESPONSES TO FUTURE UNCERTAINTY

By

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A THESIS

Submitted in Partial Fulfillment of the

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(in Forest Resources)

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The University of Maine

December 2023

Advisory Committee:

Jay Wason, Assistant Professor of Forest Ecosystem Physiology, University of Maine, Co-Advisor

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Thesis Co-Advisors: Drs. Jay Wason and Jessica Leahy

An Abstract of the Thesis Presented
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Forests provide numerous ecological and socio-economic benefits, yet climate change is creating novel and extreme conditions that threaten forests and disrupt traditional management practices. To address future uncertainty about how to manage forests amid a rapidly changing climate, researchers have developed adaptive management strategies that move away from using historical ecological baselines as management goals. However, despite increases in adaptive forest management frameworks, there are still concerns that private woodland owners (PWOs; also known as family forest owners or non-industrial private landowners) are not adopting beneficial practices. Additionally, since tree canopies often buffer understory microclimates (i.e., fine scale variation in temperature and moisture) from macroclimate extremes that occur outside of forests, there is growing interest in how forest management can be used to target specific microclimate conditions. Therefore, in order to improve forest management planning, we need to better understand how adaptive strategies can best be implemented with PWOs, in addition to understanding mechanistic links between forest management and understory conditions.

Private woodland owners represent the largest portion of national forest ownership; however, evidence suggests there may be disconnects between their climate change perceptions and behaviors, which can limit implementation of climate-focused management. We interviewed PWOs about their views of climate change and adaptive management practices, then developed a typological framework that highlights the importance of assessing their perceptions of climate-induced threats as well as their

feelings of efficacy in addressing such threats. This framework can be used when targeting communications to PWOs regarding the overlap between climate adaptive management and traditional best management practices.

Forest management operations that alter stand structure to achieve silvicultural objectives can have profound effects on understory temperature and moisture, which can in turn shape long-term stand development by promoting regeneration of certain plant species that are well suited to the microclimate conditions at a given site. We used a combination of airborne laser scanning, field-based climate data loggers, and ground-based forest measurements to demonstrate that forest structure and composition play a major role in shaping understory microclimates across spatial scales spanning the plot, stand, and landscape levels. Therefore, considering the impacts to microclimate accompanied by changes in forest structure widens the purview of forest management planning aimed at promoting adaptation and resilience to climate change.

Some silvicultural prescriptions involving prescribed fire rely on predicting understory microclimate and dead fuel moisture within a stand, which can be difficult due to high variability in these dynamic drivers of fire behavior. In this study, we used terrestrial laser scanning, field-based climate data loggers, fuel moisture sticks, and forest inventory measurements to show that forest cover buffers microclimate and increases dead fuel moisture in ways that may affect fire behavior. This research enhances fire managers' ability to plan and implement fuel treatments by highlighting how changes in forest stand structure affect fuel availability at fine scales.

Together, these studies highlight the inherent connections between management decisions and forest resilience by considering the social factors that affect decision making as well as the biophysical interactions that occur between forest stands and the climate near the ground.

DEDICATION

In loving memory of our best furry friend, Neko. He helped me establish my first field sites, he sat by my side when I wrote my thesis proposal, and he loved walking in the woods just as much as I do. His eager and curious approach to life inspires my work as a scientist every day. We miss you, buddy.

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I would like to acknowledge everyone who made this work possible as well as those who supported me through the process of completing these studies.

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I would lastly like to thank the trees, the rivers, and the mountains of the Northeast for drawing me here and for continually reminding me to pause and inquire.

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PROLOGUE

Forests account for nearly 80% of the planet's total biomass, sequester atmospheric carbon in exchange for vital oxygen, and support over 54 million jobs worldwide (Acharya et al., 2019; Li et al., 2019). Despite their importance, forests face increasing threats of damage and mortality from heatwaves, drought, and extreme weather events caused by anthropogenic climate change (Allen et al., 2010; Forzieri et al., 2022; IPCC, 2021; Pozner et al., 2022). To address future uncertainty about how to manage forests amid a rapidly changing climate, researchers have developed adaptive management frameworks and strategies that move away from using historical ecological baselines as management goals (Golladay et al., 2016; Millar et al., 2007; Nagel et al., 2017; Schuurman et al., 2020). However, despite the increase of adaptive forest management frameworks in response to climate change, there is still concern that some landowner groups are not adopting beneficial practices (Boag et al., 2018; vonHedemann & Schultz, 2021). Additionally, since forest understories are often buffered from climate conditions that occur outside of forests (De Frenne et al., 2019; De Lombaerde et al., 2022), some management operations may have profound effects on understory conditions that can be exacerbated by climate change (Zellweger et al., 2020). Therefore, in order to effectively prepare forests for novel climate conditions, there is a need to better understand how adaptive management strategies can best be implemented across a diverse range of land ownerships, as well as how extreme climate conditions interact with existing forest structure to produce unique understory conditions. In the following chapters, we use an interdisciplinary approach to broadly understand how forest management decisions affect forest responses to climate change. Together, these chapters highlight the inherent connections between management decisions and forest resilience by considering the social factors that affect decision making as well as the biophysical interactions that occur between forest stands and climate conditions near the ground where much of forest biodiversity is harbored (Sanczuk et al., 2023).

In Chapter 1, we assess private woodland owners' knowledge and attitudes toward climate change, and how these concerns (or lack thereof) affect their implementation of forest management practices that promote climate change adaptation and mitigation. Private woodland owners (PWOs; also known as family forest owners or non-industrial private landowners) represent the largest portion of national forest ownership

(Butler, 2018). However, evidence suggests there may be a disconnect between PWOs' climate change perceptions and behaviors, which can limit implementation of climate-focused management practices. We conducted 17 semi-structured interviews in Maine to develop a typological framework of PWOs based on their perceptions of climate-induced threats and efficacy. Our results produced three types of PWOs: the Steady As They Go landowner (low perceived threat), the Science-Driven landowner (high perceived threat; high efficacy), and the Seeking Support landowner (high perceived threat; low efficacy). This typological framework can be used when targeting communications to PWOs regarding the overlap between climate adaptive management and traditional best management practices. While all three types of PWOs regularly implemented resistance and resilience practices, their attitudes toward transition practices (i.e. assisted migration) diverged based on their perceptions of threat and efficacy. These divergent attitudes toward transition practices highlight the notion that adaptive practices can be both intentional and incidental. For example, Steady As They Go landowners were hopeful about the economic opportunity to grow high-value central hardwoods (e.g. various oak and hickory species) outside of their current range in Maine, while Science-Driven landowners viewed assisted migration as an adaptive tool that can be used to increase the climate resilience of threatened stands. Although Seeking Support landowners often exhibited similar levels of concern as Science-Driven landowners about climate change threats, they rarely implemented transition practices due to lacking a sense of efficacy. Our findings suggest that outreach efforts should better understand PWO perceptions of climate change threats and their feelings of efficacy in responding to such threats. When combined with knowledge about the overlap between traditional best management practices and new climate-adaptive strategies, managers can tailor their messaging to better meet PWOs at their level of climate concern.

While climate change is already negatively impacting forests, most climate projections models on which we rely for management planning are based on macroclimate conditions measured by weather stations that exist in open areas outside of forests (De Frenne et al., 2021). These conditions do not accurately reflect the conditions that exist near the ground within forests (Geiger et al., 2012). In order to better predict the effects of climate change on forests, we must downscale our view of climate by understanding how forest stands interact with weather conditions to produce distinct microclimate (i.e., temperature and moisture) conditions in understories (Chen et al., 1999; Fridley, 2009). Moreover, forest management operations that alter stand structure to achieve silvicultural objectives can have profound secondary effects on understory temperature and moisture, which can in turn shape long-term stand development by promoting certain plant species that are best adapted to the microclimate conditions at a given site (Sanczuk et al., 2023; Zellweger et al., 2020). Such feedbacks between forest structure, composition, and microclimate suggest that forest managers should consider how operations that alter stand structure may expose understories to extreme climate conditions in unintended ways (Ehbrecht et al., 2017).

Therefore, in Chapter 2 we seek to better understand how management driven changes to stand structure affect understory microclimates. We used a combination of airborne laser scanning, field-based climate data loggers, and ground-based forest measurements to determine the extent to which forest stand structure and composition drive understory microclimate buffering in different times of year. Additionally, we sought to determine the effectiveness of remotely sensed measurements for predicting landscape-level microclimate buffering across a diverse range of managed stands. Our results demonstrate that forest understory microclimates are strongly buffered against macroclimate extremes compared to unforested sites (De Frenne et al., 2019; Díaz-Calafat et al., 2023; Kašpar et al., 2021). Our study shows that forest structure and composition play a major role in shaping understory microclimates across spatial scales spanning the plot, stand, and landscape levels. We found canopy openness to be the primary driver of understory microclimate buffering (Ehbrecht et al., 2019; von Arx et al., 2013), while higher levels of evergreen cover increased the effect of canopy openness on microclimate buffering in spring. Our spatial models from airborne laser scanning show that the effects of forest management on understory microclimate are dependent upon the spatial scale (i.e., plot-level versus stand-level) at which they are considered. For example, stands that contain relatively few gaps are more highly buffered overall, with relatively little variation in buffering across the stand. On the other hand, stands that have higher proportions of gaps are still somewhat buffered at the stand-level, but with more microclimate heterogeneity. From this information, we conclude that forest management planning in a warming climate should consider the effects on microclimate buffering that accompany changes to forest structure aimed at increasing understory light (De Frenne et al., 2021; Sanczuk et al., 2023). At the same time, forest management operations can leverage the buffering effect of forest canopies to manage for climate refugia through the strategic maintenance of highly buffered zones (Díaz-

Calafat et al., 2023; Pradhan et al., 2023). Therefore, considering the impacts to microclimate accompanied by changes in forest structure widens the purview of forest management planning aimed at promoting adaptation and resilience to climate change.

In Chapter 3, we build on our findings from the previous chapter to better understand how forest stand structure impacts fuel availability by moderating understory microclimate and dead fuel moisture. We chose to investigate the relationships between forest structure, microclimate, and dead fuel moisture because these interactions can drastically impact managers' abilities to carry out silvicultural prescriptions related to fire and fuels management (Jolly et al., 2015). While predicting the conditions that contribute to fire spread are central to fire and fuels management (Cohen & Deeming, 1985; Rothermel, 1983), dynamic drivers of fire behavior (i.e., temperature, relative humidity, and dead fuel moisture) are difficult to parameterize in models due to their high spatial and temporal variability (Parsons et al., 2011; Schroeder & Buck, 1983). Despite the strong influence of within-stand structural variation on factors affecting fire behavior, quantifying forest structure at fine spatial scales (sub-plot level) is challenging with traditional forest inventory methods (Loudermilk et al., 2012; Parsons et al., 2011; White et al., 2013). Terrestrial laser scanning (TLS) is an emerging technology that can address this issue by using lidar to generate forest structure quantifications that capture more variability than traditional methods (Gallagher et al., 2021; Loudermilk et al., 2012; Maxwell et al., 2023). In this study, we used TLS, field-based climate data loggers, fuel moisture sticks, and forest inventory measurements to examine the relationships between forest structure, microclimate, and dead fuel moisture. We found strong evidence of forest structure interacting with the fire environment in ways beyond that of just being fuel. Our findings demonstrate that dense forest cover reduces fuel availability by buffering microclimate (De Frenne et al., 2019; De Lombaerde et al., 2022) and increasing dead fuel moisture (Barberá et al., 2023; Cawson et al., 2017; Tanskanen et al., 2006). The strong influence of forest structure on understory conditions is further supported by our models showing that TLS-derived variables were better predictors of dead fuel moisture than traditional forest inventory metrics, presumably due to the ability of TLS to quantify fine scale structural variation that is not captured in traditional inventories (Gallagher et al., 2021; Loudermilk et al., 2012; Parsons et al., 2011). Given the ease, efficiency, and effectiveness of using TLS to estimate forest structure, our results support the use of this emerging technology for refining landscape-level models of microclimate and dead fuel moisture to improve fire danger calculations and fire risk assessments.

Much in the same way that trees respond to their local environments while simultaneously altering their abiotic surroundings through shading and transpiration, we see in the following chapters that forest management decision making is impacted by climate change while concurrently affecting the ways that forests may experience novel conditions brought on by climate change. When viewed in this way, it is clear that adaptive forest management in an increasingly uncertain future must be attuned to both social and biophysical drivers of change.

CHAPTER 1: HOW DO PRIVATE WOODLAND OWNER PERCEPTIONS OF THREAT AND EFFICACY DETERMINE MANAGEMENT RESPONSES TO CLIMATE CHANGE?

1.1 Introduction

Forests provide numerous ecological and socio-economic benefits, yet anthropogenic climate change is creating novel and extreme conditions that threaten forests as well as traditional sustainable management practices (Allen et al., 2010; Forzieri et al., 2022; IPCC, 2021; Schuurman et al., 2020). To address future uncertainty about how to manage forests amid a rapidly changing climate, researchers have developed adaptive management frameworks and strategies that move away from using historical ecological baselines as management goals (Golladay et al., 2016; Nagel et al., 2017). However, despite the increase of adaptive forest management frameworks in response to climate change, there is still a perceived lack of implementation in small-scale private woodlands. In order to develop communication tools to increase climate adaptation in small-scale private forest ownerships, we must improve our understanding of how private woodland owners perceive the threats that climate change poses to their properties as well as their perceived efficacy in implementing adaptive management practices (McGann et al., 2022; Soucy et al., 2020). Here, we explore factors affecting the attitudes and behaviors that private woodlands owners exhibit toward climate change and adaptive forest management. By combining qualitative interview data, psychosocial theory of threat and efficacy, and typological analysis, this study provides insights for better understanding and communicating with private woodland owners about adaptive management in response to climate change.

1.2 Literature Review

1.2.1 Climate adaptation frameworks in forestry

There are two major pathways for forest management to address climate change: adaptation strategies and mitigation strategies. Adaptation strategies are driven by the desired future conditions of a forest or stand (Janowiak et al., 2014). Forest managers can seek to maintain current conditions amid climatic change ("resistance"); they can proactively alter the system in anticipation of future conditions ("transition"); or they can manage to allow for some flexibility in the system while maintaining the major structural components ("resilience") (Millar et al., 2007). On the other hand, mitigation strategies seek to use the forest's ability to sequester atmospheric carbon dioxide through photosynthesis to reduce greenhouse gasses that drive climate change. Managers can strategically promote certain trees or stands based on their ability to capture atmospheric carbon dioxide (Ontl et al., 2020). In this study, we use *adaptive management*, *adaptive practices* and *adaptive behaviors* to include any type of forest management action that is motivated by a response to climate change. While management strategies that promote climate change adaptation and mitigation have been implemented across a range of forest ownerships (Nagel et al., 2017; Peterson St-Laurent et al., 2021), they are still under-utilized in small-scale private woodlands (Janowiak et al., 2020; McGann et al., 2022).

1.2.2 Private woodland owners and climate change

Private woodland owners (PWOs; also known as family forest owners or non-industrial private landowners) include individuals, families, trusts, estates, and any other unincorporated group that owns private forestland (Family Forest Research Center, 2020). In the United States, PWOs control more forest land than any other group, representing over 260 million acres (greater than one-third) of woodlands in the country (Butler, 2018). PWO management decisions have large cumulative effects on forest fragmentation, habitat connectivity, and broadscale ecological functioning (Family Forest Research Center, 2020). Despite their large portion of ownership, the basis by which PWOs choose to manage their land is still poorly understood (Huff et al., 2017; Silver et al., 2015).

Given the large effect of private woodland owners on the forested landscape, it is important to understand how their attitudes and behaviors toward climate change influence their management practices. In some instances, PWOs were simply not concerned about climate change (Butler & Butler, 2016; vonHedemann & Schultz, 2021). In other cases, landowners have voiced clear concerns about climate change, but these concerns did not necessarily translate into adaptive behaviors (Boag et al., 2018; Sousa-Silva et al., 2016). Furthermore, some PWOs—especially those that have experienced negative effects of climate change on their woodlands—do report being concerned, which can in turn promote adaptive behaviors (Hengst-Ehrhart, 2019; Lenart, 2014).

Information and structural barriers can limit implementation of adaptive management practices (Andersson et al., 2017; Charnley et al., 2010; Grotta et al., 2013; Hashida & Lewis, 2019; Soucy et al., 2020). PWOs often report feeling that they lack information about how to effectively execute specific adaptation and mitigation strategies (Grotta et al., 2013; Soucy et al., 2020). Structural barriers are also commonly reported, such as lack of markets and financial incentives for adaptive management (Andersson et al., 2017; Charnley et al., 2010; Hashida & Lewis, 2019). Interestingly, landowners' ecological views may actually disincentivize them from implementing proactive management, due to their trust in the capacity of nature for self-repair (Ambrose-Oji et al., 2020; Bissonnette et al., 2017).

1.2.3 Theoretical frameworks for understanding psychosocial drivers of climate adaptation

In addition to pragmatic and resource-based constraints to climate adaptation in small-scale private woodlands, there are psychosocial factors that affect the attitudes and behaviors that PWOs exhibit toward climate-adaptive forest management. Rapid changes in climate pose the potential threat of uprooting forest-based livelihoods and severing attachments to familiar species compositions (Fischer et al., 2022; Weiskopf et al., 2020). Therefore, individuals must assess these potential threats and make decisions about how to act appropriately (Blennow et al., 2012). Given this natural progression from assessment to action, conceptual frameworks that include variables of *threat* and *efficacy* could improve our understanding of how PWOs may develop attitudes and behaviors toward climate change and adaptive management.

In particular, conceptual frameworks stemming from Protection Motivation Theory (PMT; Rogers, 1975) could improve our understanding of how individual perceptions of threat and efficacy influence PWO adaptations to climate change. The Extended Parallel Process Model of Fear Appeals (EPPM; Witt(Jansujwicz et al., 2013; Juerges et al., 2020)e, 1992) asserts that a perceived threat triggers a control response; from there, perceived efficacy triggers a danger control process (protection motivation), whereas perceived lack of efficacy triggers a fear control process (defensive motivation). In the context of messaging intended to change individual behaviors, danger control responses are theorized to promote message acceptance while fear control responses are theorized to promote message rejection. While EPPM has predominantly been used to evaluate public health messaging intended to promote public adoption of certain behaviors (Birmingham et al., 2015; Maloney et al., 2011; Reno & Dempsey, 2023), the core tenets of threat and efficacy have shown promise for understanding public perceptions of climate change (Grothmann & Patt, 2005; Sarrina Li & Huang, 2020; Xue et al., 2016).

The Model of Private Proactive Adaptation to Climate Change (MPPACC; Grothmann & Patt, 2005) builds upon PMT and EPPM to explicitly explain psychosocial factors determining individual adaptive actions to address climate change. Inputs into MPPACC (*risk perception* and *perceived adaptive capacity*) are closely related to *perceived threat* and *perceived efficacy* from EPPM. However, MPPACC expands on the EPPM's fear control processes by explaining resultant behaviors in the context of climate adaptation, rather than simply describing message acceptance or rejection. MPPACC describes fear control processes as avoidant maladaptive behaviors, such as fatalism, denial, and wishful thinking. On the other hand, danger control processes lead to the implementation of adaptive behaviors (Grothmann & Patt, 2005).

1.2.4 Using a typological approach to describe differences in climate change perceptions among private woodland owners

To make inferences about PWO attitudes and behaviors toward climate change and adaptive management, it could be helpful to classify landowner attitudes and behaviors using a typological approach. Typologies are commonly used in psychology and sociology to differentiate groups within a population based on particular defining characteristics (Mandara, 2003). In turn, improved understanding of group characteristics can inform policy decisions and improve outreach efforts (Jansujwicz et al., 2013; Juerges et al., 2020). In the context of PWOs, typologies have been used to understand different landowner values and priorities when it comes to owning and managing forested land (Butler et al., 2007; Ross-Davis & Broussard, 2007). Understanding the distinctions between groups of PWOs is essential for effectively tailoring forest management services and recommendations (Ficko & Boncina, 2013; Finley & Kittredge, 2006; Starr et al., 2015). In existing typologies of climate change perceptions among PWOs, landowners differed based on their level of concern about climate change, as well as their preferred mitigation strategies (Karppinen et al., 2018; Khanal et al., 2017). However, there have been no typological studies of PWOs explicitly based on *threat* and *efficacy* as they relate to perceptions of climate change and adaptive management. Given the utility of typologies for categorizing variation within a population, we seek to understand if this method could be used to better understand the attitudes and behaviors that private woodland owners exhibit toward climate change and adaptive forest management.

The goal of this study is to support outreach and communication efforts with PWOs regarding the impacts of climate change and benefits of adaptive management. To achieve this goal, we pursued three research objectives: 1) Determine if a threat-and-efficacy theoretical framework is useful for constructing a PWO typology based on their perceptions of climate change and adaptive management; 2) Identify if and how climate change concerns affect their management practices; and 3) Explore the incentives and barriers that influence their adaptive behaviors.

This study fills critical gaps in knowledge that aid in supporting managers with the implementation of climate change adaptation and mitigation strategies in small-scale private woodlands. Furthermore, this study provides the first known typology of PWOs that focuses primarily on climate change attitudes and adaptive management behaviors. These results will help extension and outreach professionals identify groups that are receptive to certain communication strategies. Private woodland owners that engage directly with our research will find a common language that can be used to better communicate the effects of climate change on their woodlands. Finally, establishing working relationships between scientists and PWOs in Maine creates discourse about adaptive forest management practices and sheds light on available resources for implementing these practices.

1.3 Methods

1.3.1 Qualitative approach

In order to effectively capture the level of nuance inherent in assessing different psychosocial drivers of climate adaptation we used an in-depth qualitative approach for this study (Bliss and Martin 1989; Bissonnette et al., 2017). By interacting directly with participants through semi-structured interviews, we sought to better understand distinctions that are otherwise quite subtle(Llewellyn et al., 2004) (Patton, 2015; Creswell, 2013). While our analyses were largely supported by theoretical frameworks from EPPM and MPPACC, our approach also used emergent themes from qualitative data to iteratively refine conceptual frameworks throughout the research process (Strauss and Corbin, 1998). In combination with qualitative coding and further creation of conceptual themes, this approach aimed to efficiently create a landowner typology and analyze differences in landowner approaches to climate adaptation.

1.3.2 Study location and participants

Our study was located in Maine, USA (Figure 1.1), which is the most heavily wooded state in the country with 89% of the total land area covered by forest (U.S. Forest Service, 2019). Maine has nearly 80,000 PWOs, who own over half of the state's forested land and account for nearly 25% of the state's annual harvested timber (U.S. Forest Service, 2019; State and Private Forestry Fact Sheet, 2023). The state is located along the Gulf of Maine, which is in the top five percent of fastest warming bodies of water in the world (Karmalkar & Horton, 2021). Climate change is most noticeably affecting Maine through milder winters, longer growing seasons, and more extreme weather events denoted by large precipitation events interspersed with periods of intense drought (Janowiak, 2018, Fernandez et al., 2020).

All study methods were conducted in compliance with the University of Maine Institutional Review Board for the Protection of Human Subjects. Participants were recruited by self-selection sampling (Llewellyn et al., 2004), in which advertisements were placed in the Maine Woodland Owners' newsletter and Maine Forest Service Woods Wise Wire email listserv. Maine Woodland Owners is a statewide non-governmental organization with approximately 3,000 members, while the Maine Forest Service listserv included 6,210 recipients at the time of recruitment. Prior to conducting interviews, we

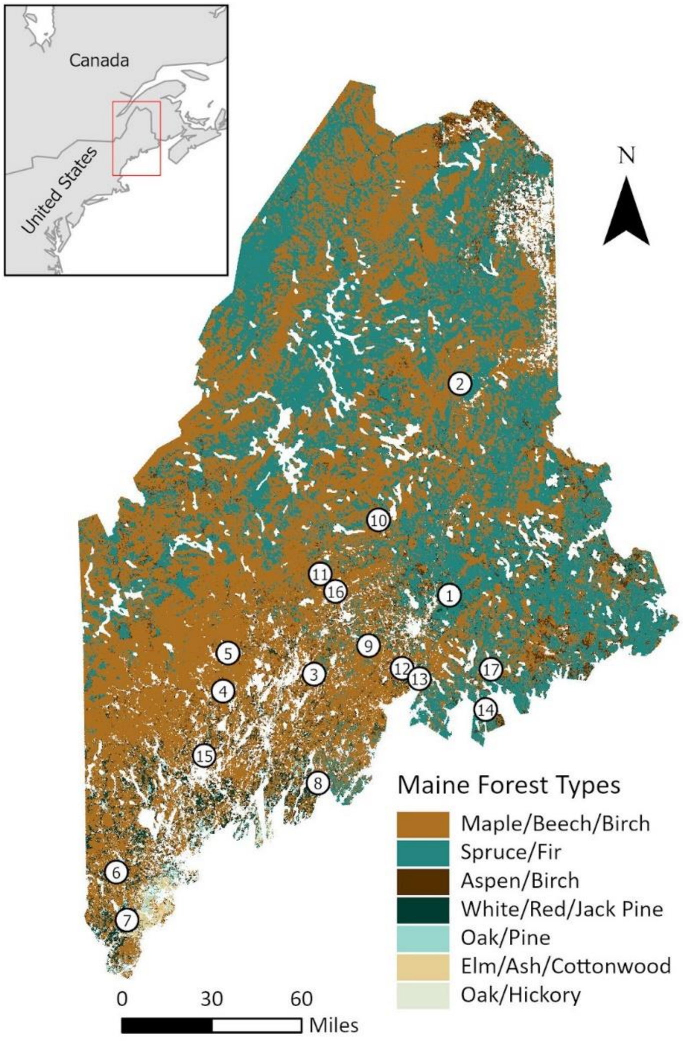


Figure 1.1 Map of study area. Map shows Maine, USA and its location in North America (inset), as well as approximate locations of private woodland owner interviews. Numbered symbols correspond to the identification code (PWO#) used for participant quotes. Map is symbolized to show the modeled distribution of Maine's major forest types (U.S. Forest Service FIA & GTAC, 2008).

engaged with potential interview candidates to address their questions, establish possible times for interviews, and share materials for transparency (i.e. consent form, interview questionnaire). Due to our self-selection recruitment process, our study sample mostly consisted of highly engaged forest landowners who had an interest in discussing their attitudes toward climate change and forest management. Although our participants are not necessarily representative of the full spectrum of PWOs in Maine, their high level of interest and engagement allowed for in-depth, fruitful discussions about psychosocial drivers of climate adaptation in small-scale private woodlands.

1.3.3 Data collection and sample description

We conducted a total of 17 semi-structured interviews from August 2022 to October 2022. Interviews occurred at participants' properties located throughout Maine (Figure 1.1). Our study participants consisted of woodland owners with property sizes ranging from 20 to 970 acres. Nearly two-thirds of participants were over 65 years old, while the remainder were 35-64 years old. Females made up 12% of participants and males made up 88%. For race and ethnicity, 82% of participants were white, 6% were American Indian or Alaska Native, and 12% reported an ethnicity not provided on the survey ("other"). Nearly half of participants had a higher degree in natural resources or professional experience related to forest management (e.g worked as a professional forester or arborist). Additionally, nearly half of participants had a consulting forester, while one-fourth had no consulting forester and one-fourth wrote their own management plans.

Our interviews focused on three key topics: 1) Past management, in order to establish baselines regarding individual landowner values and management preferences; 2) Climate change perceptions, where we explored concerns (or lack thereof) about climate change threats to their woodlands; and 3) Future plans, in order to understand if climate change is altering the ways they intend to manage their forests moving forward (see Appendix A for full interview guide). Although we used a pre-written questionnaire to guide the interviews, all questions were open-ended, which allowed for exploration of unique topics that were of interest to each respondent. The interview questionnaire was pre-tested on two PWOs in February 2022 who were not included in the official 17 participants. The questionnaire was then further refined based on feedback from these PWOs, as well as other researchers and forestry professionals.

Most interviews were conducted while walking through participants' woodlands, which allowed for vivid depictions of forest management practices and climate-related impacts to the land. Interviews were continually conducted until data saturation was reached (i.e. no new codes or themes were identified). All interviews were recorded and subsequently transcribed; the written transcripts were then used as data sources for qualitative coding.

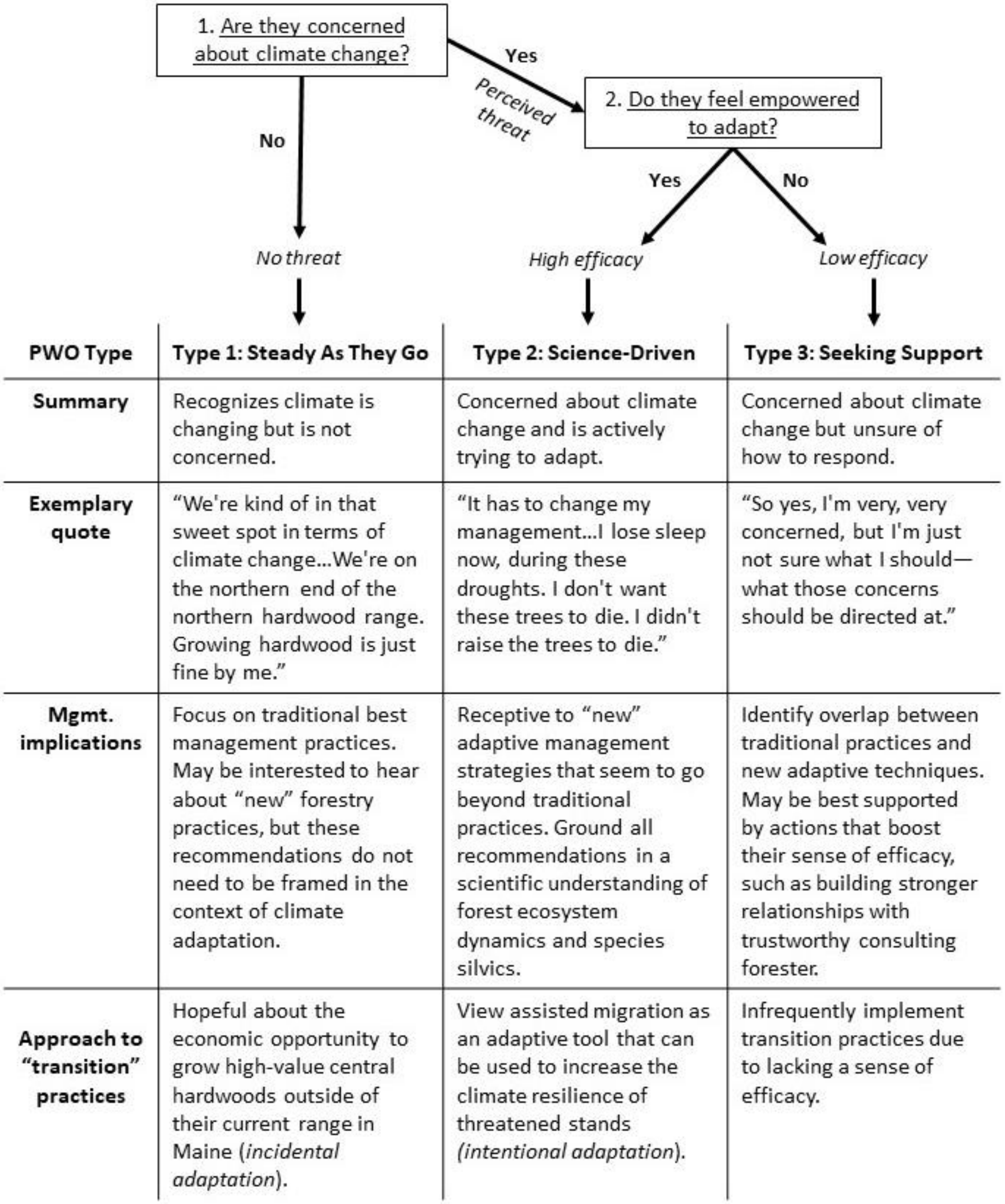
1.3.4 Data analysis

Interview data were analyzed using open and thematic coding in Taguette (Version 1.3.0, Remi Rampin and Taguette contributors, 2018), in addition to memo writing (Saldaña*,* 2009). For creation of the landowner typology, we used our theoretical frameworks to inform codes via a two-step question: 1) Is the participant concerned about climate change (i.e. is there a perceived threat)? and 2) Do they feel empowered to adapt (i.e. is there a perceived sense of efficacy)? This led to the creation of over 40 qualitative codes which were grouped into three conceptual themes of *landowner identity and core values*, *climate change threats*, and *efficacy*. Using the Ideal Type Analysis process described by Stapley et al. (2022), we used our thematic codes to summarize the narrative of each interview (i.e. "case reconstruction"). We then compared and contrasted these case reconstructions to identify groups of cases (i.e. "ideal types") based on emergent patterns among the narratives and qualitative codes (Stapley et al., 2022). From these analyses we identified three key landowner types present in our study: the Steady As They Go landowner, the Science-Driven landowner, and the Seeking Support landowner.

To identify relationships between climate change perceptions and forest management practices, we analyzed the management preferences of each landowner type across a spectrum of adaptation options. Here, we used the *resistance, resilience, transition* framework from Millar et al. (2007) as a guide, and also coded interview responses to differentiate between *intentional* and *incidental* adaptations. We defined intentional adaptations as those in which the participant's actions were motivated by perceived climate change threats, while incidental adaptations were not motivated by perceived threats yet still may increase the forest's adaptability to climate change. While discussing adaptation options, participants regularly brought up perceived and realized factors affecting their management decision-making. From these portions of the interviews, we derived codes for the incentives and barriers that were discussed.

1.4 Results

1.4.1 Objective 1: Private woodland owner typology based on perceptions of climate change and adaptive management



PWO Type	Type 1: Steady As They Go	Type 2: Science-Driven	Type 3: Seeking Support
Summary	Recognizes climate is changing but is not concerned.	Concerned about climate change and is actively trying to adapt.	Concerned about climate change but unsure of how to respond.
Exemplary quote	"We're kind of in that sweet spot in terms of climate change...We're on the northern end of the northern hardwood range. Growing hardwood is just fine by me."	"It has to change my management...I lose sleep now, during these droughts. I don't want these trees to die. I didn't raise the trees to die."	"So yes, I'm very, very concerned, but I'm just not sure what I should—what those concerns should be directed at."
Mgmt. implications	Focus on traditional best management practices. May be interested to hear about "new" forestry practices, but these recommendations do not need to be framed in the context of climate adaptation.	Receptive to "new" adaptive management strategies that seem to go beyond traditional practices. Ground all recommendations in a scientific understanding of forest ecosystem dynamics and species silvics.	Identify overlap between traditional practices and new adaptive techniques. May be best supported by actions that boost their sense of efficacy, such as building stronger relationships with trustworthy consulting forester.
Approach to "transition" practices	Hopeful about the economic opportunity to grow high-value central hardwoods outside of their current range in Maine (*incidental adaptation*).	View assisted migration as an adaptive tool that can be used to increase the climate resilience of threatened stands (*intentional adaptation*).	Infrequently implement transition practices due to lacking a sense of efficacy.

Figure 1.2 Conceptual model of landowner typology based on threat and efficacy regarding perceptions of climate change and forest management.

We used themes of *landowner identity and core values*, *climate change threats*, and *efficacy* to develop a typology of PWOs based on their attitudes toward climate change and behaviors related to adaptive management (Figure 1.2; Objective 1). While all of our study participants acknowledged the presence of climate change in the region, we found that participants had differing levels of concern about climate-induced threats and their feelings of efficacy in addressing those threats. This led to the development of three landowner types: the Steady As They Go landowner, the Science-Driven landowner, and the Seeking Support landowner (Figure 1.2). Landowners of all types implemented a diverse range of forest management practices to meet a variety of climate-related and non-climate-related objectives (Objective 2). Furthermore, many of these management practices were characterized along the resistance, resilience, transition (RRT) spectrum, which is a commonly used climate adaptation framework. Notably, the use of such theoretical frameworks highlights the importance of recognizing *intentional* versus *incidental* adaptations. Finally, participants discussed a number of factors that affected their ability to implement desired management practices. Adaptive management was often induced by feelings of efficacy and empowerment, while common barriers to action included both psychosocial and logistical hurdles (Objective 3).

1.4.1.1 Landowner identities and core values

Many of our participants valued their forests as places to practice active management, as well as spaces for recreation and wildlife habitat. These participants frequently viewed themselves as stewards of their properties and sought to protect their land from development through means such as conservation easements and land tenure planning.

"Our primary goal is to see it not developed. Because other things can always happen. But once a house or houses go on a property, it's basically gone forever." (PWO-15)

Feelings of stewardship often stemmed from long-standing relationships with their woodlands and knowing the history of the landscape. Landowners reflected on landscape history by describing long-term changes in wildlife and tree species compositions, which exhibited a clear understanding of the dynamic nature of forest ecosystems. One landowner stated, *"I mean 50 years probably doesn't qualify for most people, but it does for me and I've seen enormous changes, not only in climate but also in things like insect life and bird life. The changes have been phenomenal."* (PWO-8)

While most landowners believed that active forest management aided in achieving certain goals more efficiently (i.e. crop tree growth, specific wildlife habitat creation), they simultaneously acknowledged the inherent resilience of forest systems to recover from disturbance without human intervention. A participant highlighted the interplay between hands-on and hands-off management by saying,

"Forests were doing just fine before people came along. And in large regard the idea of a healthy forest is an economic construct. Now it's fortunate or serendipitous or whatever that good, mature, closed canopy forest of long-lasting species—they're also the highest value. It works out." (PWO-9)

"I even take the kind of 'wait and see' approach on that. I mean, I went through the [spruce] budworm outbreak, and there were a lot of landowners that didn't clear cut for budworm and didn't spray and they're still cutting wood." (PWO-9)

Participants in our study engaged with a variety of information sources to inform their management. The majority of participants were involved in non-governmental organizations that support small woodlot management (e.g. Maine Woodland Owners). Participants praised these organizations for disseminating useful management-related information as well as providing opportunities to find community with other PWOs. A landowner stated,

"Well, I'm assuming you're familiar with the woodlot owners [Maine Woodland Owners]. Yeah, this is just a wonderful publication…We've learned a lot from them. You know, so having an advocacy organization is really critical. And [Administrator] just does a fantastic job." (PWO-4)

While some participants relied solely on these organizations for their management information, others engaged with primary scientific knowledge through peer-reviewed research articles and public workshops and field tours. During interviews, these science-oriented landowners exhibited their in-depth knowledge of silvicultural principles and familiarity of emerging ideas in forest management research. A participant in southern Maine described his affinity for silviculture research by saying, *"I read a lot of research. Yeah, the stuff that's written for the public is not specific enough for me…That's my thing. And especially in winter if I'm snowbound or something like that. I'll get on a topic and I'll chase down whatever I can."* (PWO-7)

1.4.1.2 Perceived climate change threats

While all participants acknowledged the presence of climate change (e.g. warming, extreme precipitation) in Maine and beyond, landowners in this study showed differing levels of concern about climate change and its effects on their woodlands. Those with low or no concern did not perceive climate change as a threat to their property. They view climate change as a natural process that is in line with historical natural disturbance regimes.

"You know, the forest never stays the same. People who talk about the balance of nature have not the faintest idea of what they're talking about. Forests are places of change and disruption." (PWO-8)

Landowners with low climate concern indicated they had experienced few climate-related impacts on their properties and see Maine as having a low vulnerability to climate change. They expected this area to have some positive benefits such as a gain of desirable hardwood species from southerly climates. Additionally, some landowners maintain that traditional best management practices (BMPs) are the key to addressing climate change, which contributes to a sense of low climate concern. As one unconcerned landowner stated,

"I'll admit I haven't followed all that closely. But it seems as though the general idea until this past year was Maine was going to be warmer and wetter. I mean, we're kind of in that sweet spot in terms of climate change…We're on the northern end of the northern hardwood range. Growing hardwood is just fine by me." (PWO-9)

On the other hand, the majority of participants stated clear concerns about the effects of climate change on their woodlands. Many landowners showed clear concerns about invasive forest pests and diseases, and many believe that climate change is driving forest invasions.

"In general [climate change] is something I'm like, super concerned about. I read about it every day. Pretty aware of a lot of things related to it. I guess, in terms of our own forests related to climate change, probably the biggest real, tangible threat I would see is related to like, insects and pathogens." (PWO-12)

"[We are] extremely concerned. You know, I think we already see significant change, really. The insect populations have changed dramatically. In the 20 years we've been here, the drought that we've experienced in the last three years has been at least out of the ordinary for Maine." (PWO-4)

Furthermore, several landowners were concerned about "big-picture" climate change (i.e. wildfires in western U.S.), even if they had not noticed any climate-related health effects on their forests.

"Well, the dryness I think is probably the biggest thing that's pretty evident…Yeah, I mean, I'm from [western U.S.] and my son lives out there. It's like burning up." (PWO-5)

Unsurprisingly, landowners that had directly experienced climate-related forest health impacts (e.g. drought stress) on their properties exhibited the highest concerns. One landowner described the role of climate change in his management decision making by saying,

"It will change—it has to change my management. And unfortunately, I'm very resistant to do that. But just at some point—I lose sleep now, during these droughts. I don't want these trees to die. I didn't raise the trees to die." (PWO-6)

During discussions about climate change, several landowners brought up the topic of forest carbon, which reflected a wide range of perspectives on the topic. Some landowners see carbon programs as creating opportunities to broaden their management, while others see it as a new way to frame and incentivize responsible forest management practices.

"So yes, I'm very much into the carbon, and I want to work that system because I can use that carbon to help pay my property taxes…If I can get some of that money and use it to buy more woodland and take more carbon out of the atmosphere. I can look myself in the mirror and feel that I'm doing the right thing." (PWO-10)

On the other hand, several landowners expressed skepticism about carbon programs having a real, additional benefit to help mitigate carbon emissions.

"And then also, now there's this argument that, you know, maybe these carbon programs just allow industry to go on polluting the way they're polluting, and say, 'Hey, we're offsetting our carbon.'" (PWO-7)

"The other concern I have is more ethical and philosophical. Because it, you know, it strikes me that there are some very serious questions about the science here. And the way that the programs are structured,

sometimes they're kind of making some assumptions and winking at folks saying, 'Well, just don't worry about it, take the money and run.' And I would be opposed to that." (PWO-4)

1.4.1.3 Perceived efficacy

Among landowners that are concerned about climate change, participants expressed differing levels of efficacy. Here, we define efficacy as whether a landowner feels they have the ability to effectively address their climate concerns through adaptive action. Participants with formal forestry or natural resources training (i.e. bachelor's degree or on-the-job training) expressed high levels of efficacy, due to knowledge of forest management and ecological principles.

"You know, I have my colleague contacts in the scientific community. And I still read a bunch of stuff, you know, unnecessarily reading journals…So I feel lucky, the way that I have a network, you know, I'm already kind of plugged in, in many ways." (PWO-14)

Similarly, landowners who engaged with primary scientific literature and emerging forestry research felt high levels of efficacy, as they viewed adaptation as an opportunity for a living experiment in their own backyards. Those who had first-hand experience with bureaucratic processes (i.e. federal grant applications) felt confident in securing additional funds for their management.

"[Applying for federal grant money] is a very bureaucratic process, but having been a bureaucrat myself, and, you know, 30 years in federal government, I understand. And luckily, it's an advantage for me, because I don't take any of this personally. I know other people just flip out, because it's very cumbersome and, you know, rigid and not very flexible at times. Because I totally get that, that doesn't bother me. I think it is helpful. Both from a technical and extension standpoint, I think that that's a really valuable role." (PWO-14)

Several factors contributed to some landowners feeling a low sense of efficacy. Participants that expressed low efficacy often mentioned feeling a lack of proper knowledge or training regarding natural resource management. This lack of information could come from having a poor relationship with their forester or feeling "out of the loop" regarding the management of their woodlot. As one landowner put it,

"So yes, I'm very, very concerned [about climate change]. But I'm just not sure what I should—what those concerns should be directed at." (PWO-5)

Other landowners that lacked efficacy mentioned feeling overwhelmed by the increasing number of invasive species on their property.

"It's on my list to deal with so many things. At least the ones that are reasonable. At least keep stuff from getting worse…You know, the invasives particularly like the Norway maple [Acer platanoides] *and the buckthorn* [Frangula alnus]*—I've just been trying to keep up with those. And I'd like to do better. But it's hard and takes time to do that. I'll go and spend 30 minutes attacking one area and, well, it looks worse than it did last year."* (PWO-12)

Another factor contributing to low feelings of efficacy was a tangible sense of pessimism about how humanity has treated the natural world, either in the past or the present. This pessimism seemed related to a sense of hopelessness about society's ability to adapt to climate change on a large scale. One participant expressed his negative feelings toward climate change by saying,

"I have a grim notion of the future, you know, seriously. Was it this week that the report came out that the Arctic ice shelf is melting seven times faster than they thought it was? And every other week, there's something just as nasty." (PWO-3)

1.4.1.4 Landowner types

Based on our study participants' perceptions of climate change threats and their feelings of efficacy regarding forest management to address such threats, three different landowner types were identified: the Steady As They Go landowner, the Science-Driven landowner, and the Seeking Support landowner (Figure 1.2).

1.4.1.4.1 The Steady As They Go landowner

The Steady As They Go landowner recognized that the climate is changing but is not concerned. This lack of concern may stem from perceived benefits of climate change or feeling that climate change is natural or inevitable.

"So, if I've seen any effect on this forest from climate change, I think it's been perhaps benign at this point. It's things like, you know, the species of birds are changing a little bit" (PWO-16)

"I don't have much faith in humans stopping climate change. I think it's gonna happen—it is happening. I think it's gonna continue to happen, to some degree. So we're just faced with it. It's a reality." (PWO-9)

"You're worried about climate change? It is inevitable...Yeah, it's been coaxed along by all this gasoline and all this…But still are we going to—is that going to change? Are people going to stop going to Maine Mall? You want to stop climate change? Bulldoze Maine Mall and everything like it. And take I-95 and dig a big hole through it and tell people they have to walk. So what's the chance of stopping climate change? Zero. Because nobody can do without their shirts and dresses." (PWO-8)

Moreover, with this type of landowner, the topic of anthropogenic climate change was potentially a cause for contention or skepticism.

"It definitely is warming. We can all see that. But I don't know. The first thing you hear is people caused it. I don't think I believe that. We're not helping, that's for sure." (PWO-2)

This assertion that humans lack a role in causing global climate change supported the Steady As They Go landowner's notion that it is a natural process that poses no greater threat than the historic range of climatic variability.

Additionally, this type of landowner was not likely to have experienced major climate-related impacts to their property. The Steady As They Go landowner was primarily concerned with threats to active forest management (logging bans and restrictions), as well as increasing numbers of forest pests and diseases.

"I think we got more problems coming from people than we do global warming. I think there's some resilience there, but we got all these diseases, longhorn beetle, emerald ash borer, of course. People forget Dutch elm, the beech scale, all those were brought in by people a long time ago." (PWO-2)

Their management was often founded on traditional BMPs; when confronted with "new" forestry practices to address climate change, they felt like they had been doing the correct management all along. This contributed to the Steady As They Go landowner feeling confident in maintaining their current management regime in the face of their perception that climate change posed a minor threat.

"Actually, this carbon sequestration is really what we've done all the time. We've tried to grow the high value species to big size–things that would be used in furniture or construction. The carbon will be stored for years. That's been our goal, without saying it in those words." (PWO-2)

1.4.1.4.2 The Science-Driven landowner

The Science-Driven landowner perceived climate change as a threat to the health of their forest and felt empowered to adapt. The Science-Driven landowner felt a high sense of efficacy by embracing the inherent uncertainty of climate change and leaning on contemporary research to guide their management. This type of landowner was willing to try "new" adaptive practices to address climate change if they were not already doing them. One landowner described their view of climate adaptation by saying,

"It's just—you got to go with the flow, kind of. You know, assisted migration is one of the biggest things...So I thought that [chestnut oak] might be a good tree that would be adaptable to changing conditions." (PWO-7)

"I'm really interested to know—in terms of management practices—what impacts the climate is going to have on the ability of this property to be healthy...So what else is coming? What else in terms of management do I need to be thinking about to keep the property healthy?" (PWO-14)

While landowners of this type had a range of relationships with their foresters, they did not rely on a forester for basic information . Some had a colleague-like relationship where they actively exchanged ideas about proper forestry practices, while others felt that they had the proper knowledge to effectively manage their property without needing a close relationship with a forester. Moreover, this type of landowner often felt a higher sense of efficacy by viewing their management relative to other landowners who they perceived to lack proper forestry knowledge and training. One landowner in southern Maine exhibited this by saying,

"The NRCS people love me because I'd already been doing some work. I already knew what I wanted to do with it, you know. They didn't have to come in and like, explain everything to me." (PWO-7)

"I think landowners are pretty much in denial about climate change. I don't think they understand the severity of it. And they don't get out on their land enough to notice it." (PWO-6)

1.4.1.4.3 The Seeking Support landowner

The Seeking Support landowner was concerned about climate change but was unsure of how to respond. They felt a low sense of efficacy due to a perceived lack of forestry knowledge or simply because the idea of addressing climate change through their management was too daunting.

"You know, if I probably knew all the ways that [my property] could be affected, I'd probably say yes to all of them. I'm concerned about it." (PWO-5)

Of the three landowner types in this study, the Seeking Support landowner was least likely to have plans for active forest management on their property. This is because they were primarily concerned with protecting their property from development and strongly believed in the power of nature to heal itself.

"I try to take a 'less is more' approach when possible. Yeah, probably because I don't have any like, really specific forestry goals. Mostly it's like, I want it to remain forested and I want it to provide wildlife habitat…So it's like, either humans are going to thin the stock or it's going to thin itself. I'm okay with it thinning itself" (PWO-12)

On a similar note, the Seeking Support landowner was keenly aware of humanity's poor track record regarding environmental issues, which may impede a feeling of efficacy about adapting to climate change.

"Honeysuckle is a predecessor of the Natural Resource Conservation Service in the 1970s. Had plant sales every year. They encouraged you to plant autumn olive, honeysuckle, highbush cranberry. I planted all three." (PWO-3)

"You know, when they did the solar field, all the animals—skunks into our backyard. And there were groups of 15 deer running across near Hannaford market when they were cutting all that through too. So that, you know, that really bothers me. That really drives me crazy. It's crazy. It's irresponsible. It's trying to fix something that they can't fix." (PWO-5)

"It's just more screwed up by people, for lack of a better term. Like, you know, with all that agricultural kind of history. I think the soil was—there's some areas where I think the soil was pretty degraded. There are places where it's like, the duff layer never really seems to build up." (PWO-12)

Interestingly, despite having such a high reliance on outside information sources for knowledge of forest management (i.e. consulting forester), this type of landowner typically lacked a close relationship with a forester. This could be due to a lack of interest on the landowner's part or due to difficulties finding foresters that adequately met the needs of the landowner.

"You know, [our previous forester's] plan said look in 20 years and we looked in 20 years and then [the new forester] came and he didn't give me much in the way of new information. Didn't do any further inventories….I walked with him and his dog the first day and then I thought I'd see him in the afternoon the second day, but he was already gone. So I just don't, I mean, he had lots of information from [the previous

forester's] plan, and I'm sure he knows what he's doing. But I didn't feel that he had a chance to really see it." (PWO-3)

1.4.2 Objective 2: Forest management preferences across landowner types

We found that landowners in our study implemented a diverse range of forest management practices to meet both climate-related and not climate-related objectives. Here, we categorize landowner management practices along the resistance, resilience, transition (RRT) spectrum to understand how their actions fit into a commonly used climate adaptation framework. Then, we discuss the motivations that drive landowners to implement these practices while highlighting the importance of recognizing *intentional* versus *incidental* adaptations.

1.4.2.1 Management along the resistance, resilience, transition (RRT) spectrum

Landowners in our study exhibited management that spanned the entire spectrum of resistance, resilience, and transition (RRT) practices. Here, we characterize resistance practices as those that are fixated on maintaining the current species composition or stocking level (i.e. invasive plant removal).

"And the other thing is this invasive, you know, the thistle that's showing up. So, you know, in terms of management, I think I and other landowners need to be more attuned to that and be more vigilant in monitoring, because the best way to deal with it is before it takes hold, right?" (PWO-14)

Resilience practices were characterized as those that intended to increase diversity of species and structure, as well as those that maintained flexibility to match changing environmental conditions (e.g. enrichment tree planting).

"I'm not after the money per se. I want the diversity of stuff…I want softwood and hardwood [in my woodlot]. Because depending upon what the future brings, the mixture of those trees is the most likely to survive what's coming." (PWO-10)

"I'm trying to keep the forest fairly diversified species-wise, and also age-wise. So if the climate changes impact a particular species of trees, it won't wipe out my whole 50 years of work." (PWO-15)

Transition practices were characterized as those that facilitated a shift in species composition or structure based on expected future conditions (e.g. assisted migration).

"The growing season is pushing a month and a half longer than it was when we came in. I planted black walnuts." (PWO-3)

"Yeah, I planted seedlings that are here now as well as some from southern New England and mid-Atlantic states." (PWO-14)

Interestingly, PWO type was not necessarily indicative of management preferences along the RRT spectrum, as all types of landowners in our study exhibited all types of practices along this spectrum. However, the most notable difference in management preferences came with regard to transition practices. Although Steady As They Go and Science-Driven landowners both implemented transition practices, the former saw climate change as an opportunity to capitalize on warming conditions by planting valuable southerly hardwood species, while the latter perceived assisted migration as a proactive measure aimed at improving the health of the stand in the face of threats from climate change. Furthermore, Seeking Support landowners participating in our study were less likely to implement transition practices, which was likely due to this type of landowner generally practicing less intensive management than the other landowner types.

1.4.2.2 Intentional versus incidental adaptation

We found that participants exhibited both intentional adaptations, which were driven directly in response to observed or expected climate-related stressors, as well as incidental adaptations that can unintentionally increase adaptive capacity to climate change. Although Steady As They Go landowners were typically not concerned about climate change impacts to their woodlands, they often capitalized on changing conditions by planting high value southerly species outside their northern range margins. Science-Driven landowners were the most likely to implement intentional adaptations on their properties. Common intentional adaptations implemented by this landowner type included assisted migration and stand density reductions in response to climate stressors such as drought. Seeking Support landowners rarely implemented intentional adaptive practices, as this absence of intentional adaptation was a major driver of their lacking a sense of efficacy. However, when guided by a close relationship with their forester this type of landowner implemented incidental adaptations, such as timber stand improvement and creation of wildlife habitat.

1.4.3 Objective 3: Barriers and incentives to adaptive management in small scale woodlands

Participants discussed a number of factors that affected their ability to implement desired adaptation and mitigation practices that address climate change. From these discussions, we identified several barriers and incentives to management that were common across all landowner types.

The most common barriers to management were related to carrying out harvest or treatment operations. Landowners often had a difficult time finding reputable contractors and repeatedly mentioned the prohibitive costs of conducting proper management.

"We had actually planned to do that harvest three years earlier, and we just had a series of things that delayed the process, and even then, we were having trouble. Part of it was finding somebody to do the logging." (PWO-4)

"It's hard to find people that are on the same thought process as you that can look at trees of value and not cut them. That's a difficult thing to find in the industry." (PWO-5)

Related to forest operations, several landowners mentioned the logistical difficulties of gaining access to parts of their properties they wanted to manage.

"There's really no easy access point. So if we were ever going to get any kind of machinery in here or something, there's really no haul road." (PWO-14)

Another common barrier included land tenure issues, as many participants had unresolved plans for the future of their properties.

"And then there's a whole other issue of succession—human succession. I have two boys, and neither one of them live here. They liked the woods, but they're not interested in managing it. So we're—my wife and I are looking at different ways, different ideas of how to transfer the land. And, you know, there's a lot of landowners in that situation." (PWO-11)

"But maybe, I mean, I'm 76 years old. Maybe it'll last and I'll let somebody else worry about it. Let my daughter worry about it." (PWO-9)

Despite the logistical hurdles inherent in conducting forest management practices, participants mentioned a number of incentives that motivated their management. Across the board, feelings of stewardship served as the most common motivator for landowners to implement desired management. This often manifested as management practices to promote wildlife habitat, as well as landowners mentioning a sense of responsibility and connection to their property.

"You know, it's an investment in the future. And we're not gonna be around forever and we're not gonna see the, you know, the long-term benefits. But our son and daughter-in-law will, and it's something we can contribute." (PWO-4)

"But I'll probably never cut any of these for money. Yeah, well, like I said, I like big trees. It's really hard in this area to find a stand of big trees that isn't like looking down a gun barrel, like going to be cut any day. Right? So, if I can create this kind of unique thing that you just don't see anymore, it's worth it." (PWO-7)

"These creatures have rights, sort of, they exist by themselves. And it's kind of a hard shift from, you know, our European colonial kind of training that these are mine." (PWO-11)

Landowners with a close relationship to their forester often perceived greater incentives for management, although several highly efficacious participants were able to implement management practices in the absence of a consulting forester. Finally, participants with lower financial constraints often had an easier time implementing desired practices, which was often achieved through participation in cost sharing programs or certain markets that were conducive to their desired forest conditions.

"Well, if you've got enough markets for the low grade, you can afford to do these management techniques. But if you don't, you're in trouble. Just especially mechanically, you got to be able to market the wood. We don't have enough pulp mills. And if we don't keep growing more sawlogs–spruce, pine, hardwoods–we're not going to have the manufacturing facilities there either. A big portion of them go to Canada now." (PWO-2)

1.5 Discussion

We found that PWOs exhibited a range of attitudes and behaviors related to climate change and adaptive management, which is consistent with existing literature. Several studies have found that there is a disconnect between climate change perceptions and behaviors in the global PWO population (Boag et al., 2018; Grotta et al., 2013; Hengst-Ehrhart, 2019; Sousa-Silva et al., 2016). Our typological framework based on perceptions of threat and efficacy offers an exciting step toward an improved understanding of this disconnect by highlighting how seemingly nuanced differences in attitudes and behaviors toward climate change among different types of PWOs can result in divergent approaches to adaptive management.

Previous typologies focusing on climate change perceptions among PWOs have mostly focused on management strategies that promote carbon storage for climate change mitigation (Karppinen et al., 2018;

Khanal et al., 2017). While most of our participants were aware of carbon markets as potential income sources, none of them were currently enrolled in a carbon credit program and many were skeptical about the current economic and ecological integrity of these programs. The few participants that were seriously considering enrolling were motivated by perceptions of contributing to a greater cause (i.e. mitigating carbon dioxide emissions) and the potential for passive income.

In addition to carbon management, we focused on adaptive practices to better understand factors affecting landowner perceptions of threat and efficacy. Study participants that had experienced the greatest impacts to their properties from climate change (e.g. drought stress, extreme storm damage) exhibited the highest levels of concern about threats posed by climate change (similar to Blennow et al., 2012). In the absence of clear climate-related impacts, several participants still perceived their properties to be vulnerable to threats such as pests, diseases, and drought stress. These feelings of vulnerability were likely major drivers of perceived threats (Füssel, 2007). For landowners that perceived climate change as a threat, feelings of efficacy tended to motivate protective action (Rogers, 1975). We found that participants expressing a sense of efficacy were often empowered by formal forestry knowledge or training, as well as access to supportive information from a forester or outreach organization. For landowners with a strong sense of stewardship, these sources of information likely bolstered their perceived adaptive capacity (Adger et al., 2009; Grothmann & Patt, 2005).

Our study participants implemented practices all along the RRT spectrum, although intentions varied depending on landowner type. While it has been shown that PWOs are amenable to implementing resistance and resilience practices (McGann et al., 2022), nearly half of participants in our study were already practicing—or seriously considering—transition practices such as assisted migration. Notably, participant approaches to transition practices highlighted the importance of distinguishing between intentional and incidental adaptations, which is supported by our typological framework. Because all of our participants recognized regional climate warming trends, their attitudes toward transition practices diverged based on their perceptions of threat and efficacy. For example, Steady As They Go landowners were hopeful about the economic opportunity to grow high-value central hardwoods (e.g. various oak and hickory species) outside of their current range in Maine, while Science-Driven landowners viewed assisted migration as an adaptive tool that can be used to increase the climate resilience of threatened stands. Although Seeking Support landowners often exhibited similar levels of concern as Science-Driven landowners about climate change threats, they rarely implemented transition practices due to lacking a sense of efficacy.

We found that barriers to adaptation were two-fold: psychosocial and logistical. psychosocial barriers were less common, although they reflected those previously discussed in the literature (Adger et al., 2009; Janowiak et al., 2020). Notably, several Seeking Support landowners expressed barriers to processing and addressing the high levels of uncertainty associated with climate change projections. On the other hand, most participants discussed logistical barriers such as finding reputable foresters and contractors, conducting harvests and other practices in an effective and efficient manner, and dealing with land tenure and legacy issues. These findings emphasize the need for technical service providers to integrate climate adaptation measures into their existing technical services by identifying its overlap with traditional best management practices and ecological forestry, and then providing the appropriate educational information to match the recipient landowner type (D’Amato & Palik, 2021).

Other studies have noted that in order to increase widespread adaptation in small-scale private woodlands, it’s not about providing *more* information, but *better* or *well-timed* information (Hengst-Ehrhart, 2019; Huff et al., 2017; Sousa-Silva et al., 2016). While most PWO management preferences fit into current climate adaptation frameworks (such as the RRT spectrum), in order to effectively tailor outreach and education efforts to landowners we recommend that managers understand the motivations that drive the implementation of these practices. In fact, it is entirely possible to implement climate adaptive management practices (e.g. assisted migration) in the absence of climate change concerns, as other factors (e.g. markets) may play a significant role in motivating such management action. Previous studies have noted that there is often much overlap between climate adaptation strategies and ecological forestry practices (D’Amato & Palik, 2021). Therefore, technical support messaging for PWOs can be improved by synthesizing concepts of ecological forestry and climate-adaptive forestry into integrated prescriptions that simultaneously meet ecological and climate adaptation goals.

In terms of management support and outreach, our study suggests that the Steady As They Go landowner will likely benefit the most from messaging focusing on traditional best management practices.

They may be interested to hear about adaptive forestry practices, but these recommendations do not need to be framed in the context of climate adaptation. Science-Driven landowners are most likely to be receptive to intentional adaptive management practices that address climate change. When discussing management techniques with Science-Driven landowners, it is advised to ground all recommendations in a scientific understanding of forest ecosystem dynamics and species silvics. When communicating with the Seeking Support landowner for outreach and educational purposes, it is advisable to focus on traditional best management practices and the basic benefits of adaptive management. This group is likely to be receptive to management practices that address climate change, although it is important to identify overlap between traditional practices and new adaptive techniques. This type of landowner may be best supported by simply taking actions to boost their sense of efficacy, such as building stronger relationships with trustworthy consulting foresters.

1.5.1 Limitations and future research

Although our sample population is not fully representative of all Maine PWOs, we believe our conceptual framework has highlighted three key types of highly-engaged landowners and their perceptions of climate change and adaptive management. Regardless, future research investigating psychosocial drivers of climate adaptation should include quantitative studies on representative sample populations of PWOs to determine how well our framework applies to these populations and to determine how PWO attitudes and behaviors change over time. While our study participants were highly engaged PWOs that consisted mostly of retired white men, this sample is generally representative of highly engaged Maine PWOs. In general, research supporting forest management and outreach efforts could be improved by including additional perspectives, such as women and gender minorities, and Indigenous worldviews.

While we found that PWO perceptions of threat and efficacy were useful for forming our typology, more explicit tests of specific MPPACC input parameters may provide greater insight for understanding PWO management responses to climate change. Specifically, future research should focus on individual drivers of "risk perception" (e.g. probability, severity, cognitive biases) and "perceived adaptive capacity" (e.g. adaptation efficacy vs. self-efficacy) as outlined in the MPPACC to better understand different types of landowners with respect to climate-adaptive forest management (Grothmann & Patt, 2005).

1.6 Conclusion

Climate change is catalyzing forest owners into considering management practices that bolster the adaptive and mitigative potential of their woodland properties (Golladay et al., 2016; Millar et al., 2007; Nagel et al., 2017; Schuurman et al., 2020). Despite their relatively large portion of forest ownership, PWOs have often been perceived to be lacking in their concern about climate change and in their implementation of adaptive management practices (Boag et al., 2018; Butler & Butler, 2016; Sousa-Silva et al., 2016; vonHedemann & Schultz, 2021). While all of the participants in our study acknowledged the presence of global climate change we found that they varied based on their perceptions of climate-induced threats, as well as their level of perceived efficacy in addressing such threats. Therefore, we developed a typological framework based on threat and efficacy to better understand how climate change perceptions drive adaptive management preferences among PWOs. Our results included three types of PWOs with regard to perceptions of climate change and adaptive management: the Steady As They Go landowner, the Science-Driven landowner, and the Seeking Support landowner. Study participants exhibited a wide range of management practices, many of which can be characterized using common climate adaptation frameworks such as the resistance, resilience, transition (RRT) spectrum. Notably, our three PWO types exhibited divergent attitudes and behaviors toward transition practices (i.e. assisted migration), which highlights the importance of recognizing *intentional* versus *incidental* adaptive behaviors. For example, Steady As They Go landowners were hopeful about the economic opportunity to grow high-value central hardwoods (e.g. various oak and hickory species) outside of their current range in Maine, while Science-Driven landowners viewed assisted migration as an adaptive tool that can be used to increase the climate resilience of threatened stands. Although Seeking Support landowners often exhibited similar levels of concern as Science-Driven landowners about climate change threats, they rarely implemented transition practices due to lacking a sense of efficacy.

Increasing our understanding of the psychosocial drivers of climate adaptation can help to inform better tools for engaging and communicating with PWOs about climate change and adaptive management. Our findings suggest that outreach and education efforts should meet landowners at their current level of climate concern by better understanding their perceptions of climate change threats and efficacy in responding to such threats. When combined with knowledge about the overlap between traditional best management practices and new climate-adaptive strategies, our conceptual framework can shed light on ways to improve communication with PWOs about climate change as well as appropriate contexts for implementing adaptive management.

CHAPTER 2: FOREST MANAGEMENT THAT MAINTAINS EVEN PARTIAL FOREST COVER IS CRITICAL FOR BUFFERING UNDERSTORY MICROCLIMATE

2.1 Introduction

Forests often buffer understory microclimate conditions (i.e., fine scale variation in temperature and moisture) compared to broader macroclimate conditions outside of forests (Chen et al., 1999; De Frenne et al., 2021; Geiger et al., 2012). Forest canopies are critical for moderating microclimates, which affects ecosystem functioning by maintaining suitable wildlife habitat (Hansen et al., 2001), driving understory plant population dynamics (Thompson et al., 1977; Zellweger et al., 2020), and sheltering tree regeneration from abiotic stress (McDowell & Allen, 2015; Will et al., 2013). However, anthropogenic climate change is also causing increases in extreme climate conditions including heatwaves, atmospheric droughts, and soil droughts (IPCC, 2021). These extreme climate conditions can negatively impact tree regeneration (Pozner et al., 2022; Stevens-Rumann et al., 2018) and overstory trees (Allen et al., 2010; Forzieri et al., 2022). Therefore, understanding the drivers of microclimate variation will aid in predicting forest ecosystem responses to novel climatic conditions (De Lombaerde et al., 2022; Morelli et al., 2016; Zellweger et al., 2020).

Although extreme climate conditions are increasing in many parts of the world, forest canopies can buffer understory microclimates from macroclimate extremes (De Frenne et al., 2019; Frey et al., 2016). This buffering effect is largely driven by canopy leaves and branches absorbing solar radiation that would otherwise penetrate the forest floor, which results in closed canopy conditions reducing daily temperature fluctuations by as much as 4-8 °C compared to open conditions (Ehbrecht et al., 2019; von Arx et al., 2013). In temperate mixedwood forests that contain both evergreen needle-leaved and deciduous broadleaved trees (Kenefic et al., 2021), the proportion of evergreen cover has been suggested to be especially important for maintaining buffering in winter (Díaz-Calafat et al., 2023). However, little is known about how mixedwood forests buffer understory microclimates throughout annual cycles of leaf-on to leaf-off conditions.

Forest management can alter stand structure and composition through timber harvesting and precommercial operations, which also changes understory solar radiation and moisture availability (Aussenac, 2000). Although the focus of forest management is often related to creating appropriate light conditions for regeneration, there are profound effects on other aspects of the understory microclimate that also impact understory biota. Therefore, there is growing interest in how forest management can be used to target specific microclimate conditions (Ehbrecht et al., 2017; Menge et al., 2022). For example, in temperate deciduous broadleaved forests, larger canopy gaps resulted in higher understory temperatures and lower understory humidities compared to smaller canopy gaps (Latif & Blackburn, 2008). There is also evidence to suggest that understories in even-age managed systems are less buffered than uneven-age systems, which are still less buffered than unmanaged systems (Menge et al., 2022). Interestingly, even though uneven-age and unmanaged systems often have more heterogenous stand structures than those in even-age systems (Menge et al., 2022), stand structural complexity does not appear to be an important predictor of understory microclimate (Ehbrecht et al., 2017, 2019). By improving our understanding of mechanistic links between forest management and understory microclimates, we can better understand how current management regimes impact the climate resilience of future stands.

Quantifying microclimate buffering at management relevant scales is challenging (Díaz-Calafat et al., 2023; Menge et al., 2022; Zellweger, De Frenne, et al., 2019). However, remote sensing technologies show promise for improving our understanding of the relationship between forest management and microclimate buffering by upscaling plot-level measurements to stand and landscape scales (Zellweger, De Frenne, et al., 2019). For example, remotely sensed lidar and spectral data have been used to estimate forest metrics such as canopy height, density, and evergreen cover at scales ranging from less than 0.05 hectares to over 2 million hectares (Ayrey et al., 2019; Bhattarai et al., 2022; Woods et al., 2008). When combined with ground-based measurements of understory microclimate conditions, they can be used to predict microclimate buffering beyond the plot level (Jucker et al., 2018; Kašpar et al., 2021; Menge et al., 2022). While a handful of studies have used such approaches to estimate landscape-level microclimate buffering, they tend to be focused on mountainous areas where microclimate is largely driven by topography (Jucker et al., 2018; Menge et al., 2022; Vandewiele et al., 2023), or they are limited to a single season (Kašpar et al., 2021; Vandewiele et al., 2023), a single forest type (Kašpar et al., 2021; Menge et al., 2022), or a single management regime (Kašpar et al., 2021; Vandewiele et al., 2023). Therefore, determining the mechanistic influence of forest structure and composition on microclimate buffering—and how these relationships vary throughout the year across a diverse range of managed stands—is essential for developing adaptive management strategies that minimize the negative effects of climate change on forest understories (Greiser et al., 2018; Zellweger, Coomes, et al., 2019).

Here, we use a combination of airborne laser scanning, field-based climate data loggers, and ground-based forest measurements to better understand how management driven changes to stand conditions affect understory microclimates. Specifically, our research objectives are: 1) determine the extent to which forest stand structure and composition drive understory microclimate buffering in different times of year; and 2) determine the effectiveness of remotely sensed measurements for predicting landscape-level microclimate buffering across a diverse range of managed stands. This research provides forest managers with information about how stand conditions may affect regeneration outcomes in the face of climate change.

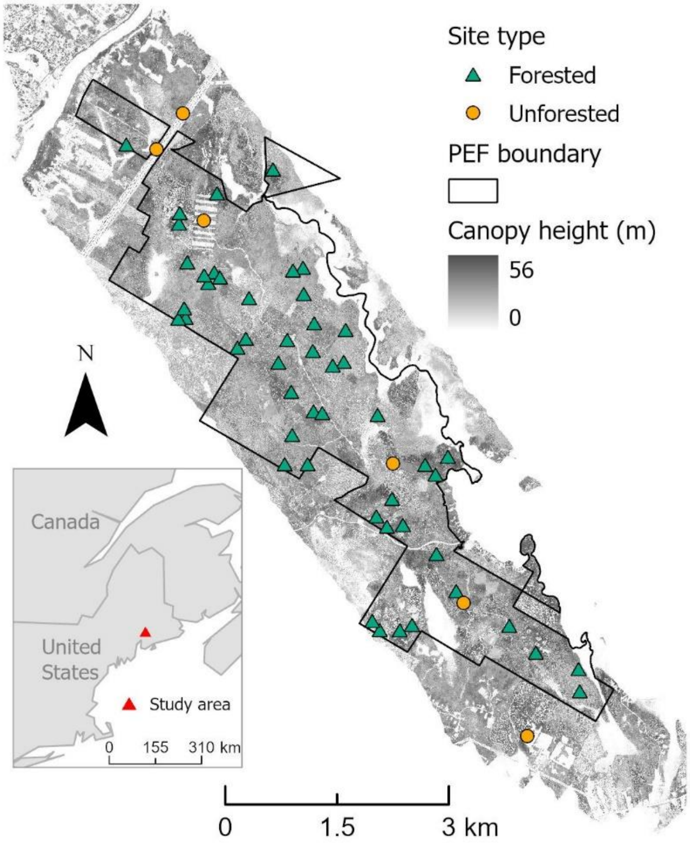


Figure 2.1. Study area map of the Penobscot Experimental Forest (PEF) in Bradley, Maine. Symbols depict 60 study sites (two not pictured) established across a broad range of forest structures and compositions. Each site included a 10-meter fixed radius forest inventory plot design with a microclimate sensor located at plot center. The unforested sites were established at least 30 meters from a forest edge in clearcuts and landings inside the PEF in addition to nearby open fields. Map shading represents lidar-derived canopy height model obtained from NASA G-LiHT flight in August 2021.

2.2 Methods

2.2.1 Study area and site selection

This study focused on the Penobscot Experimental Forest (PEF) in central Maine, USA, which is a long-term silvicultural research forest managed by the USDA Forest Service Northern Research Station (Figure 2.1). The PEF contains over 50 individual management units (MUs) that have received a range of experimental harvesting treatments, from high basal area removal (i.e., commercial clearcut) to low basal area removal (i.e., single tree selection), as well as intermediate treatments (i.e., thinning). Additionally, stand-level species compositions range from pure evergreen needle-leaved to pure deciduous broadleaved, with many mixed stands interspersed. Common species include red spruce (*Picea rubens*), balsam fir (*Abies balsamea*), northern white cedar (*Thuja occidentalis*), eastern white pine (*Pinus strobus*), eastern hemlock (*Tsuga canadensis*), red maple (*Acer rubrum*), northern red oak (*Quercus rubra*), paper birch (*Betula papyrifera*), bigtooth aspen (*Populus grandidentata*), and American beech (*Fagus grandifolia*). The PEF has relatively uniform topography, with a total elevation difference of nearly 75 meters from the lowest to highest point (Figure B.1).

In order to select sites that captured a broad range of stand structures and compositions, we identified potential locations for our 52 forested study sites by compiling existing forest inventory data from over 700 long-term permanent sample plots (PSPs). Using the most recent inventory measurements (2009-present), we stratified all PSPs into quartiles of basal area and evergreen cover basal area, resulting in 16 strata within which we randomly selected three to four sites. We excluded sites that were within 100 meters of a previously selected site. Furthermore, to avoid their potential effects on microclimate conditions, we excluded PSPs that were within 30 meters of a major gravel road or within 150 meters of a major water body. To quantify how forested sites differ from macroclimate conditions, we established eight additional unforested sites within 6 kilometers of the PEF (Figure 2.1). Unforested sites had little or no canopy cover and were at least 30m from a forest edge.

2.2.2 Microclimate data

To quantify microclimate conditions at each site, we split sites into intensive sites (one per strata and four unforested; 20 total) and extensive sites (two or three per strata and four unforested; 40 total). Microclimate conditions were measured using iButton data loggers (Hygrochron model DS1923, resolution 0.5 °C and 0.6% RH; Thermochron model DS1921G, resolution 0.5 °C; Maxim Integrated Products, Inc., Sunnyvale, California). Hygrochrons logged air temperature and relative humidity at intensive sites every two hours, while thermochrons logged soil temperature every four hours at intensive sites or air temperature every four hours at extensive sites. All loggers were synchronized to log at 13:00 EDT. To minimize exposure to solar radiation and precipitation while allowing for adequate air mixing, each iButton logger was suspended inside a vented radiation shield with additional overhead radiation cover (modified from Wason et al., 2017) and fastened to a wooden post one meter above the ground (pictured in Figure B.3). Posts were oriented so that radiation shields were on the south side of the stake and iButtons for soil temperature (intensive sites only) were secured in latex balloons for water protection and buried to 10 cm on the south side of posts. Sensor arrays remained in the field from December 2021 to September 2023.

All microclimate time series data were inspected, and we removed anomalous events (such as logger malfunctions and interference with sensor arrays from wildlife or fallen trees) that were clearly incongruous with nearby sites (4.1% of logger-days removed). Our final microclimate dataset included measurements from December 15, 2021 to August 31, 2023.

2.2.3 Ground-based forest measurements

To acquire up to date forest structure and composition measurements at each site, we conducted fixed-radius, nested plot surveys (10-meter outer radius; 6-meter nested radius). We recorded diameter at breast height (DBH) and species of all trees greater than 11 centimeters DBH within each outer plot, and all trees greater than 1 centimeter DBH within each nested plot. For each site, we calculated total basal area, trees per hectare, and evergreen cover basal area (Table 2.1). We also calculated canopy openness at each site by computing the mean of four measurements taken in cardinal directions with a spherical densiometer (Forestry Suppliers Spherical Crown Densiometer, Convex Model A; see Beeles et al., 2022) held directly over each iButton logger (Table 2.1).

Table 2.1 Summary of ground-based forest structure and composition measurements. All metrics are derived from 10-meter fixed radius plots surveys of all trees greater than 1 centimeter diameter at breast height (DBH). Evergreen cover is calculated as a percent of total plot basal area. SD is standard deviation.

Measure	Mean	Max	Min	SD
Basal area (ft^2/acre)	129	285	0	±68
Trees per acre	1625	5901	0	±1211
Canopy openness (%)	21	99	0	±31
Evergreen cover (%)	63	99	15	±21

2.2.4 Remotely sensed forest measurements

To determine the ability of remotely sensed forest metrics to predict understory microclimate, we quantified forest structure from high density (>12 pulses/m^2) lidar data gathered for the PEF and nearby unforested sites in August 2021 using the Lidar Hyperspectral & Thermal Imager (G-LiHT) operated by NASA's Goddard Space Flight Center (Cook et al., 2013). All lidar points were classified into ground and non-ground points and were further used to create a digital elevation model (DEM) and normalized point cloud. We used the DEM to extract topographical metrics (i.e., elevation and aspect; Figure B.1). We used the normalized point cloud to generate height and intensity metrics (Roussel et al., 2020) as well as a canopy cover estimate calculated from the percentage of all returns over the mean height of each pixel (Table B.1). In addition to structural metrics derived from lidar data, we used spectral indices derived from Sentinel-2 satellite imagery to estimate forest composition. Sentinel-2 multispectral data with less than 30% cloud cover were acquired from USGS's Earth Explorer archive in 2021. From these data, we extracted Normalized Difference Vegetation Index (NDVI) and a four-band composite of the blue, green, red, and near-infrared bands. Additionally, we created a Principal Component Analysis composite containing principal components (PCs) 1 and 2, which explained 94.24 and 5.76% percent of the variance, respectively. All remotely sensed variables were calculated at the plot level (10-meter radius clipped to match ground-based plots) as well as wall-to-wall across the entire PEF.

2.2.5 Data analyses

For each site, we calculated daily values of maximum and minimum air temperature (T_{max} and T_{min}), which were used to calculate daily temperature range (DTR = T_{max} - T_{min}). Daily temperature range is an ecologically significant metric that captures microclimate buffering of both maximum and minimum temperatures (Figure B.2; Ehbrecht et al., 2019; Menge et al., 2022; Thompson et al., 1977). At intensive sites, we calculated daily maximum vapor pressure deficit (VPD_{max}) from relative humidity and temperature. Daily values of DTR and VPD_{max} were further summarized by meteorological season [i.e., winter (December, January and February), spring (March, April and May), summer (June, July and August), and autumn (September, October and November)] for use in a subset of our models.

To compare microclimate buffering between forested and unforested sites across seasons, we calculated seasonal means of DTR (n=60) and VPD_{max} (n=20) for each forested and unforested site and conducted Welch's t-tests of the means for each season. Next, we split our analysis into a series of ground-based models and remote-sensing based models to investigate the extent to which forest stand structure and composition drive understory microclimate buffering in different times of year. For the ground-based models, we created a series of linear regression models that related our ground-based forest structure metrics to daily and seasonal mean daily DTR and VPD_{max}. While our initial analyses included canopy openness, evergreen cover, basal area, and stand density (trees per hectare), we found that basal area and stand density were correlated with canopy openness and explained relatively small amounts of variation in microclimate when compared to the remaining predictors. Therefore, and in line with other recent studies on forest microclimates (Díaz-Calafat et al., 2023), we used canopy openness and evergreen cover as the two candidate predictors for our ground-based models.

To determine how daily variation in DTR or VPD_{max} was driven by forest structure and composition, we built a set of ground-based linear mixed effects models predicting daily DTR or VPD_{max} within each season as a function of canopy openness and evergreen cover as fixed effects. We included a random effect for site and a first-order autoregressive term for temporal autocorrelation. We first allowed canopy openness and evergreen cover to interact, and if that interaction was not significant ($\alpha < 0.05$) it was removed from the model and we only assessed main effects.

Due to large day-to-day variation in DTR and VPD_{max} we also tested how we could predict their seasonal means (n = 47-58 sites per season for DTR; n = 18-20 sites per season for VPD_{max}) in a set of linear models including canopy openness and evergreen cover (and their potential interaction) as predictors.

In order to visualize the daily variation in model performance, we also fit daily linear models across our entire dataset predicting DTR (n = 47-58 sites per day) or VPD_{max} (n = 18-20 sites per day) as a function of canopy openness and evergreen cover as fixed effects (interactions excluded because they were relatively rare and to ease interpretation).

In order to determine the effectiveness of airborne measurements for predicting landscape-level microclimate buffering, we created a series of random forest (RF) models that could be used to predict DTR across the entire range of management conditions at the PEF. Here we focus only on DTR (rather than also VPD_{max}), where we have an adequate number of sites for the more complex model fitting procedures. Using an area-based approach described by White et al. (2013), these seasonal RF models leveraged explanatory variables derived from airborne lidar and Sentinel-2 (Table B.1) to predict DTR across the study area for each season. To select the best predictors for each seasonal model, we initially grew a random forest with all possible variables. Then we used bootstrapping to select the ten best predictor variables by including those that were used the most for predictions and by removing those that were highly correlated. Once each seasonal model was defined, we resampled all variables (Table B.1) using 10-meter^2 pixels (the coarsest resolution among our predictors) for wall-to-wall estimates. We then created a raster stack of these estimates, which was used to predict DTR across the entire PEF at 10-meter resolution. We assessed model fit via root mean square error (RMSE), mean bias, coefficient of variation (CV) and a pseudo-R^2 derived from linear models of observed versus predicted values (Table B.5).

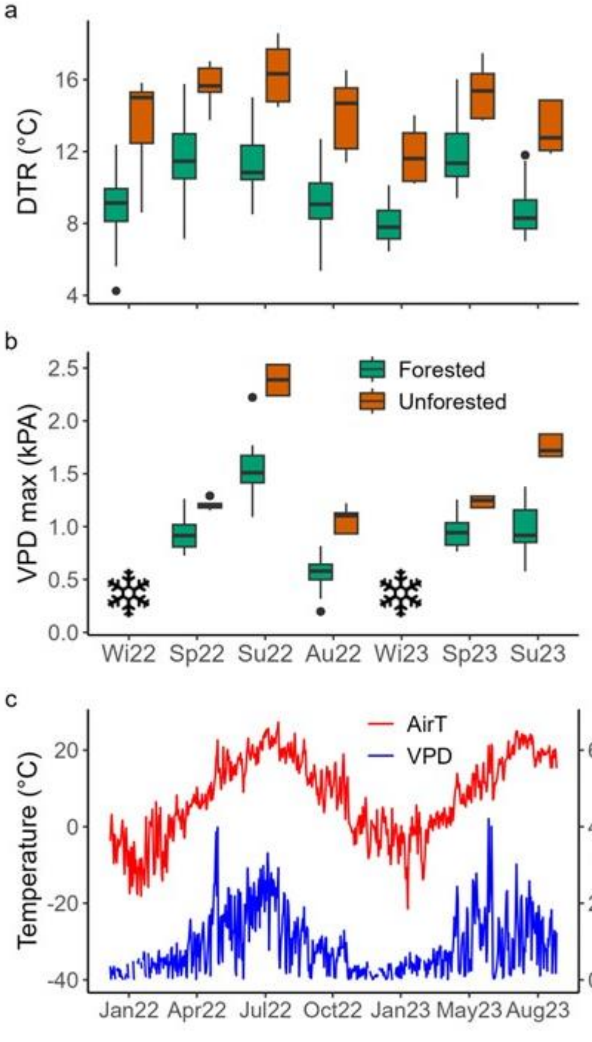


Figure 2.2 Microclimate summaries. a) Seasonal summaries of daily temperature range (DTR) and **b)** daily maximum vapor pressure deficit (VPD$_{max}$) for forested and unforested sites across the study area. Season-year is shown on the x-axis, where Wi = winter, Sp = spring, Su = summer, and Au = autumn. **c)** Daily values of mean temperature (AirT) and maximum vapor pressure deficit (VPD) averaged across all sites for the entire study period.

In order to compare microclimate buffering across forest management regimes, we extracted predicted values of DTR from seven representative MUs at the PEF. The first set of representative MUs are part of a PEF compartment study comparing the long-term ecological outcomes of different management regimes, including unmanaged reserves, exploitative treatments, and silvicultural regeneration methods. Additionally, we chose a second set of representative MUs from the Acadian Forest Ecosystem Research Program (AFERP), which is a long-term silvicultural study examining the ecological outcomes of natural disturbance-based treatments (Carter et al., 2017; Seymour et al., 2002). The representative

AFERP MUs included an unmanaged reference, large gap treatment, and small gap treatment. Geospatial vector layers were obtained from publicly available databases via the USDA, Maine GeoLibrary, and USGS National Hydrography Database. All data analyses were conducted in R (R Core Team, 2021).

2.3 Results

Overall, we found that forested sites had significantly lower DTR (mean difference of 4.31 °C) and VPD_{max} (mean difference of 0.55 kPa) than unforested sites across all months (*p-value* < 0.001; Figure 2.2a and 2.2b). Generally, in unforested sites the highest values of DTR occurred in spring and summer when the mean value was 15.18 °C. In contrast, DTR in forested sites was much lower throughout the year (mean of 10.03 °C) with the highest values occurring in spring (mean of 11.72 °C; Figure 2.2a). VPD_{max} was higher in

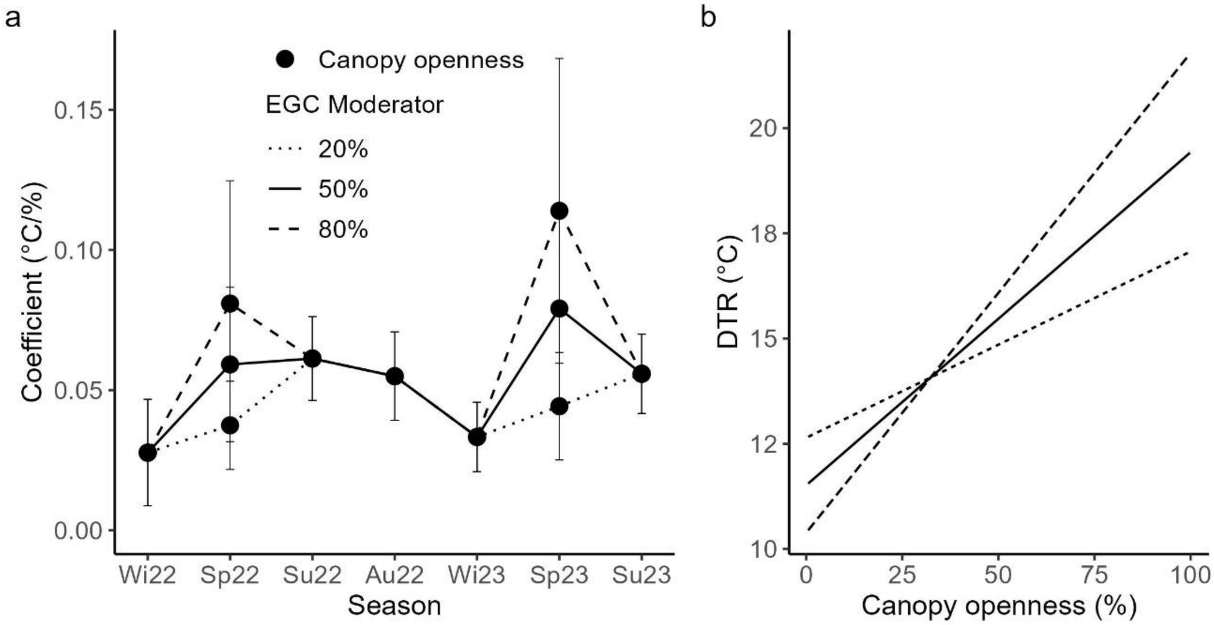


Figure 2.3 Ground-based model coefficients. a) Coefficients for canopy openness (CO) in seasonal models of daily temperature range (DTR) that also included evergreen cover (EGC). Model formula was DTR ~ CO * EGC when there was a significant interaction (Spring only) and DTR ~ CO + EGC when there was no significant interaction (all other seasons). Dotted lines represent values of the interaction moderator when significant interactions occurred between CO and EGC. Filled point symbols denote significant non-zero coefficients ($p < 0.05$). Bars represent one standard error. **b)** Partial plot of CO shown for different levels of EGC moderator.

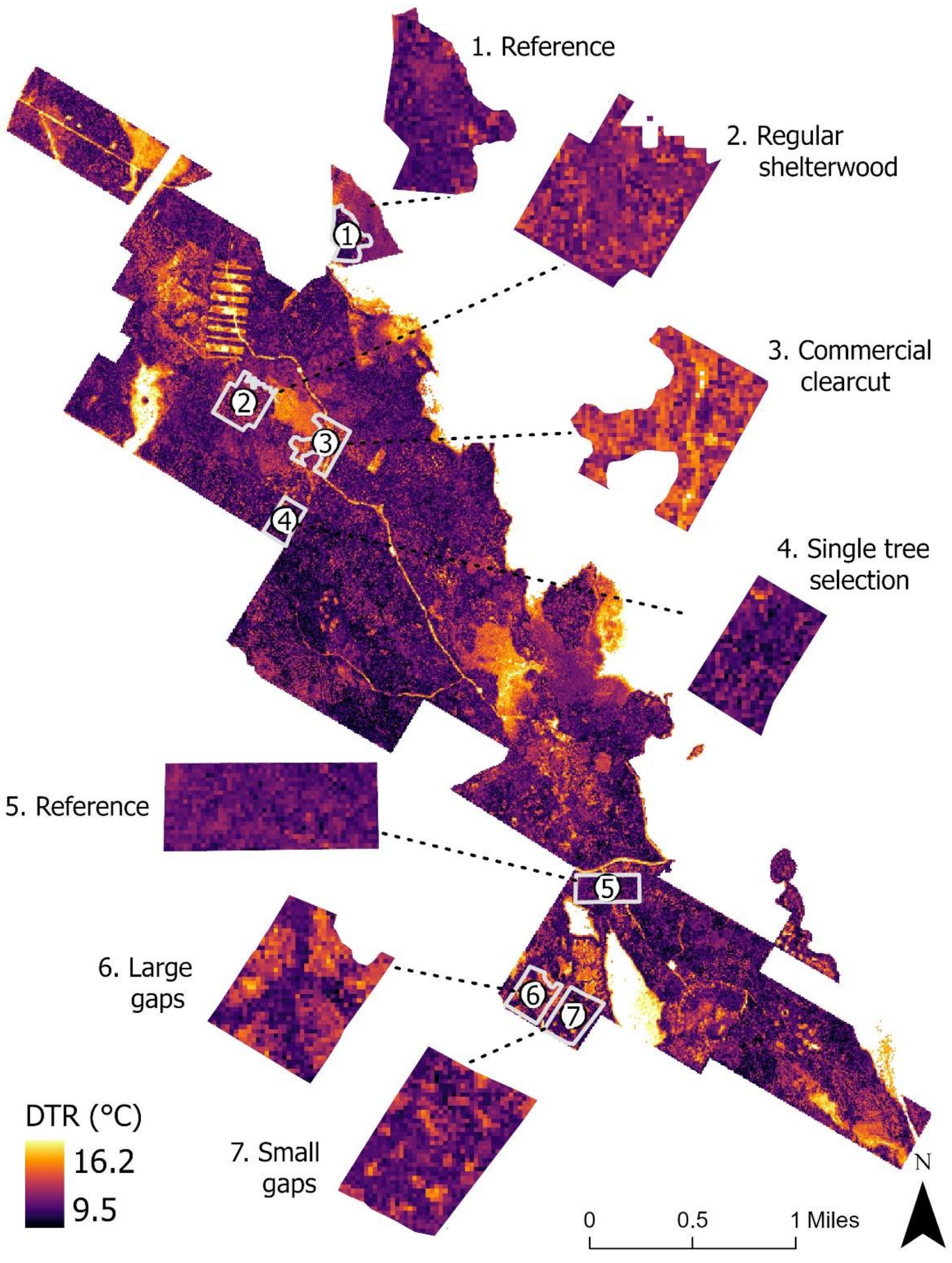


Figure 2.4 Model-predicted daily temperature range (DTR) across the Penobscot Experimental Forest. Pixel size is 10x10 meters. Overlaid are management units selected as examples for subsequent analyses, which represent a range of treatments used to compare the effects of management systems on DTR. Figure represents modeled values of DTR from Summer 2022.

unforested sites, with the most prominent difference occurring in summer when unforested sites regularly exceeded 2 kPa (mean of 2.11 kPa) and forested sites had a mean VPD_{max} of 1.25 kPa (Figure 2.2b). Notably, the highest VPD_{max} across all forested and unforested sites occurred in July of each year (mean of 1.81 kPa), with the next highest values occurring in May of each year prior to leaf development (mean of 1.66 kPa; Figure 2.2c).

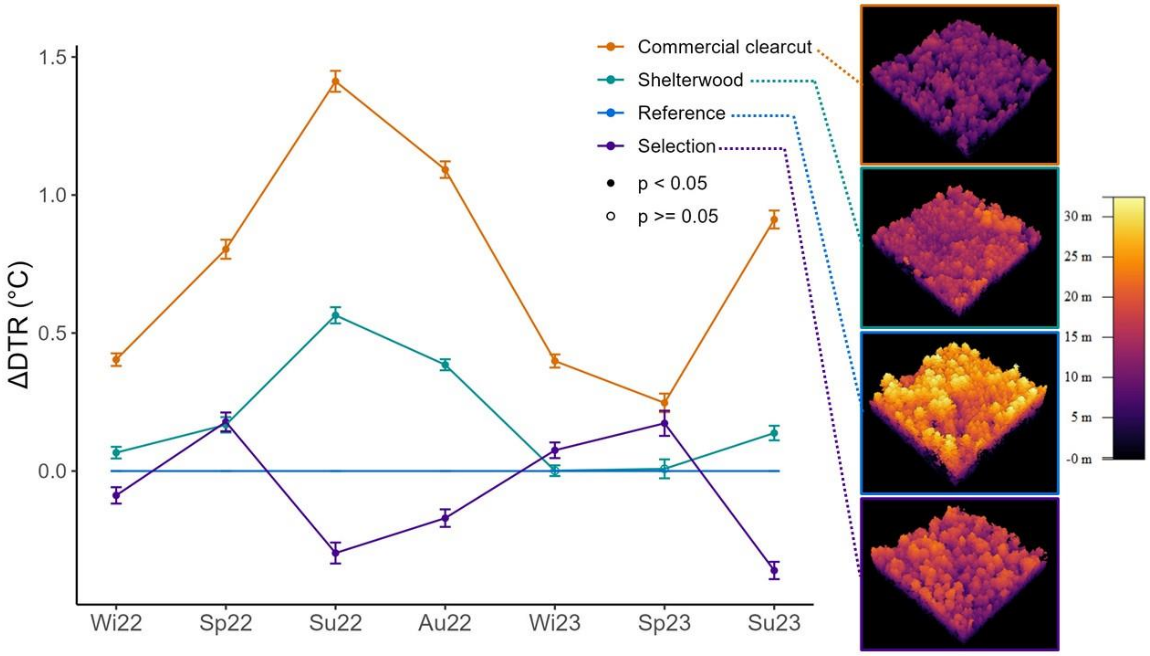


Figure 2.5 Difference in predicted daily temperature range (ΔDTR) between three representative management units (MUs) and a representative reference MU at the Penobscot Experimental Forest (PEF) for each season of the study period. Filled point symbols denote a significant difference from the reference ($p < 0.05$). Standard error is shown for each treatment in each month. Normalized point clouds representing 1 ha (100x100m) are shown on the right for each example MU, which are colored to show height of lidar returns (scale bar on right).

AIC model selection for ground-based models suggested that there were many roughly equivalent models (mean of 20 models within 10 AIC of the best model). To reduce model complexity, we removed predictors with high collinearity and focused on predictors that previous literature suggests show a mechanistic link to understory microclimate and appeared in most of the top models. Thus, for our subsequent analysis on seasonal patterns we used models predicting DTR and VPD_{max} as a function of canopy openness, evergreen cover, and the potential interaction between the two. In our first set of models predicting daily or seasonal mean DTR and VPD_{max} we found that linear mixed models (LMMs) using daily values of DTR (Table B.2) and VPD_{max} (Table B.4) produced very similar coefficients to linear models (LMs) using seasonal means of DTR (Table B.3) and VPD_{max} (Table B.5). We saw relatively consistent R^2 across seasons; however, the R^2 from the daily models (range: 0.027-0.184; Tables S2, S4) were often much lower than the R^2 from the seasonal mean models (range: 0.394-0.797; Tables S3, S5).

When modeling DTR as a function of ground-based estimates of canopy openness and evergreen cover, we found that increased canopy openness significantly increased DTR in all seasons (Figure 2.3a). However, there was no consistent effect of evergreen cover. Instead, we found that evergreen cover interacted with canopy openness in the spring with higher levels of evergreen cover leading to a stronger effect of canopy openness on DTR (more positive slope; Figure 2.3b). For models of VPD_{max}, we found that increased canopy openness drove significant increases in VPD_{max} in summer and autumn. However, VPDmax in spring was only significantly reduced by evergreen cover (Figure B.4).

Finally, to determine how forest management impacts DTR, we used random forest models that

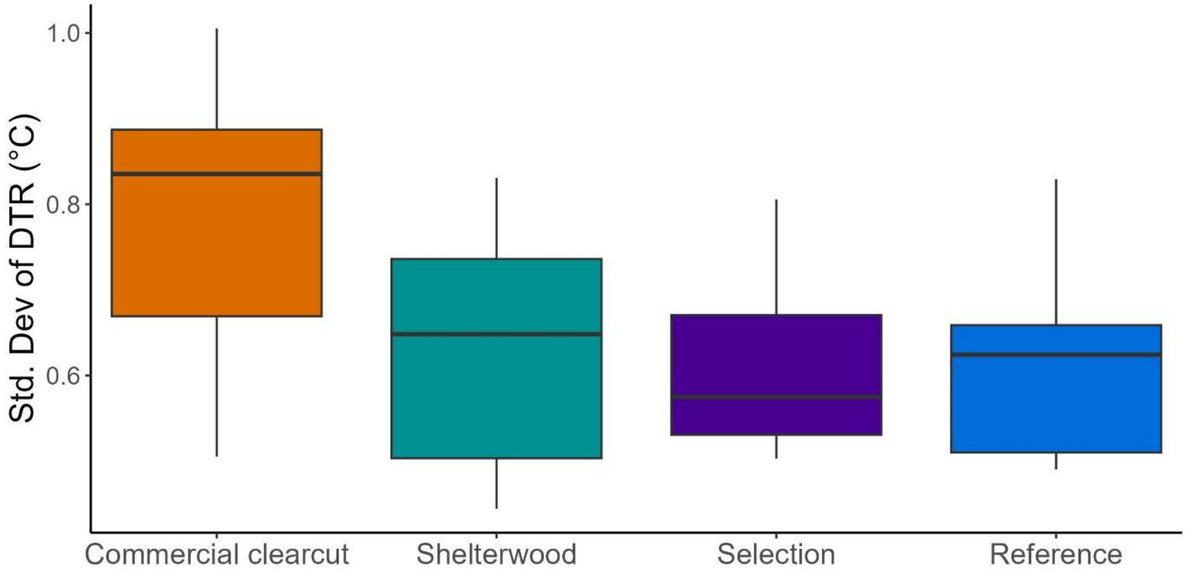


Figure 2.6 Standard deviation of predicted daily temperature range (DTR) across all seasons between four representative management units (MUs) at the Penobscot Experimental Forest. Standard deviations of DTR were calculated from all pixels within each representative MU of raster prediction map.

included lidar and spectral data at 10-meter resolution across the entire study area to predict DTR. We found that the models performed best in summer and autumn (mean pseudo-R^2 0.53; Table B.5) compared to winter and spring (pseudo-R^2 0.29; Table B.5). When comparing modeled DTR across representative MUs in summer 2022 (Figure 2.4) we found that when compared to a nearby unmanaged reference stand, the MU that received the exploitative treatment (i.e., commercial clearcut) had up to 1.41 °C higher daily temperature fluctuations in summer (Figure 2.5) and more within-stand variability in DTR throughout the year (Figure 2.6). In contrast to the commercial clear cut, DTR in even-age (i.e., shelterwood) and uneven-age (i.e., single tree selection) treatments varied from the reference stand by less than 0.57 °C in all seasons (Figure 2.5) and showed comparable within-stand variability in DTR compared to the reference (Figure 2.6). Relative to two different expanding gap treatments (small and large gaps) we found that the large gap treatment showed the highest mean values of DTR (especially in the summer; Figure 2.7) and the greatest heterogeneity in DTR

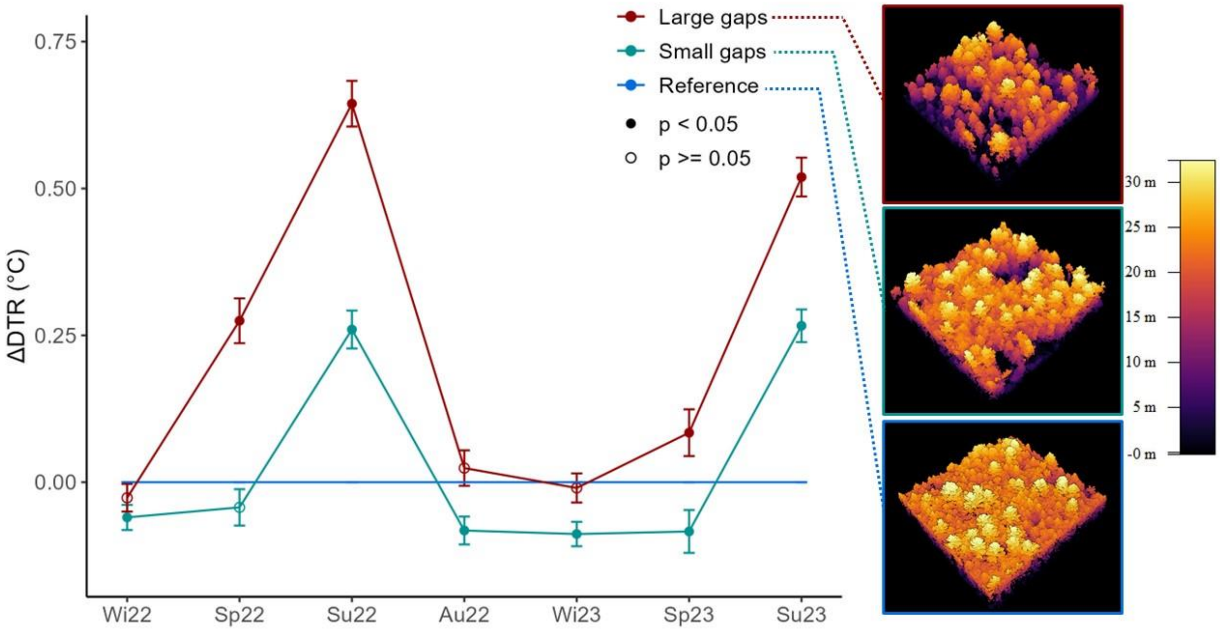


Figure 2.7. Difference in predicted daily temperature range (ΔDTR) between two representative gap treatments and a representative reference at the Penobscot Experimental Forest (PEF) for each season of the study period. Filled point symbols denote a significant difference from the reference ($p < 0.05$). Standard error is shown for each treatment in each month. Normalized point clouds representing 1 ha (100x100m) are shown on the right for each example MU, which are colored to show height of lidar returns (scale bar on right). These representative management units are part of the Acadian Forest Ecosystem Research Program (AFERP), which is a long-term silvicultural research project examining the ecological outcomes of expanding gap irregular shelterwood treatments.

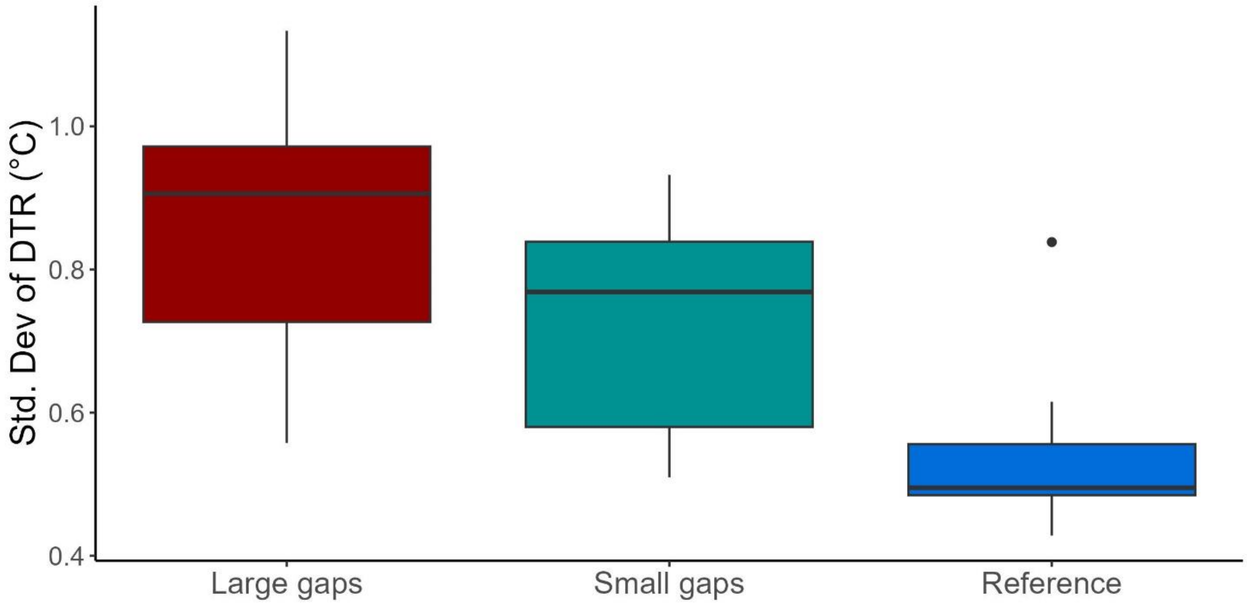


Figure 2.8 Standard deviation of predicted daily temperature range (DTR) across all seasons between two representative gap treatments and a representative reference at the Penobscot Experimental Forest. Standard deviations of DTR were calculated from all pixels within each representative management unit of the raster prediction map. These representative management units are part of the Acadian Forest Ecosystem Research Program (AFERP), which is a long-term silvicultural research project examining the ecological outcomes of expanding gap irregular shelterwood treatments.

(Figure 2.8). However, the magnitudes of these effects were less than half the magnitude of the commercial clearcut (Figure 2.5) and DTR matched the reference in autumn and winter (Figure 2.7). The small gap treatment was intermediate between the large gap and refence treatment in summer DTR and did not differ from the controls in the other seasons (Figure 2.7).

2.4 Discussion

Overall, our results support other research demonstrating that forest understory microclimates are strongly buffered against macroclimate extremes compared to unforested sites (De Frenne et al., 2019; Díaz-Calafat et al., 2023; Kašpar et al., 2021). We found that buffering (DTR in our study) is largely driven by reductions in T_{max}, and in lesser part, by increases in T_{min} (Figure B.2). We also find evidence for a threshold effect whereby buffering of forest understories is maintained with as much as 60% canopy openness but declines rapidly beyond that. It appears that this buffering is also maintained into the spring (but not fall or winter) for stands that have higher proportions of evergreen cover. Therefore, forest management strategies that maintain even partial forest cover are critical for buffering understories from climate extremes (De Lombaerde et al., 2022). While certain silvicultural systems (i.e., even-age) rely on reducing or removing the overstory to initiate regeneration of new cohorts, forest management operations in a warming climate must consider the secondary effects of harvesting on understory microclimate buffering (Díaz-Calafat et al., 2023; Menge et al., 2022, Pradhan et al., 2023).

Our study shows that forest structure and composition play a major role in shaping understory microclimates across spatial scales spanning the plot, stand, and landscape levels. Similar to previous studies (Ehbrecht et al., 2019; von Arx et al., 2013), we found that canopy openness is the primary driver of understory microclimate buffering explaining 38-71% of variation in DTR depending on the season. The mechanistic link between canopy openness and buffering is clear; however, forest management planning often considers basal area as well. Therefore, we note here that basal area also emerged as a significant predictor in some of our early models. However, given its relatively high correlation with canopy openness (r = -0.79), lower ability to predict buffering, and limited mechanistic link to buffering we instead focused on canopy openness. Therefore, future research that aims to include basal area in predictions of microclimate from forest structure should test the relative effects of canopy openness and basal area on buffering.

We found that higher levels of evergreen cover increased the effect of canopy openness on microclimate buffering in spring. Díaz-Calafat et al. (2023) previously found that evergreen cover interacts with canopy closure to influence temperature buffering in the winter. However, they compared only the warmest and coolest months of the year and they also used canopy openness and basal area interchangeably as measures of forest density. Our study builds on their findings by examining these relationships throughout the entire year, and our findings shed light on springtime as a crucial period. As spring temperatures increase to approach early summer conditions, lengthening days lead to increased solar radiation and understory warming. In stands containing a mix of evergreen and deciduous trees, sites containing evergreen trees are more buffered than sites with deciduous trees, which have still not leafed out for the season. While deciduous-dominated sites may have increased light availability in the understory which can be beneficial for some spring ephemeral herbs (De Pauw et al., 2022), sites that lack evergreen trees may experience high understory temperatures and VPDs relative to sites with more evergreen trees. Therefore, it is important to recognize the potential vulnerability of deciduous-dominated sites in the event that climate change increases extreme heat and drought conditions in the springtime when buffering for these sites is reduced.

The accuracy of our spatial models (mean pseudo-R^2 of 0.53 in summer and autumn) for predicting landscape-level microclimate buffering were within the range of many previously reported values (range: 0.51-0.57) (Jucker et al., 2018; Kašpar et al., 2021), but they were less accurate than others (Menge et al., 2022). Additionally, our models show that both structural (i.e., lidar) and compositional (i.e., spectral) metrics are useful for predicting landscape-level microclimate buffering. While there are likely many factors influencing model accuracy, future research that aims to predict landscape-level microclimate buffering from remotely sensed data should test the effect of spatial resolution (i.e., pixel size) on prediction accuracy. Since forest structure and composition often vary at fine scale within a stand, it may be assumed that higher spatial resolutions would result in higher model accuracy. However, it is worth noting that even when ground-based measurements are recorded at a similar scale to the raster data (i.e., 10-meter fixed radius plots and 10-meter pixels), the pixel grid may not be aligned with the ground measurements in a way that produces high correlations between predicted and observed values. Therefore, future research should also consider ways to address the potential mismatches between ground-based measurements and overlaid raster grids. While higher resolution remote sensing data may improve predictive power, it also comes with tradeoffs related to data storage and processing times.

Finally, our models show that the stand-level effects of forest management on understory microclimate are dependent upon the spatial scale (i.e., plot-level versus stand-level) at which they are considered. In mesic forests that are predominantly closed canopy, microclimate heterogeneity is driven by canopy gaps that increase light penetration to the understory yet also decrease understory buffering (Latif & Blackburn, 2008; Muscolo et al., 2007). Stands that contain relatively few gaps are more highly buffered overall, with relatively little variation in buffering across the stand. On the other hand, stands that have higher proportions of gaps are still somewhat buffered at the stand-level, but with more microclimate heterogeneity. Menge et al. (2022) found that understory microclimates in even-age and uneven-age managed stands more closely resembled each other than microclimates in unmanaged stands, even when they considered even-age stands across all stages of rotation. This is likely due to the unmanaged stands having the densest canopies (i.e., multi-layered), as these stands were approaching old-growth structure but still not experiencing much canopy disturbance (Fraver et al., 2009; Menge et al., 2022).

From this information, we conclude that forest management planning in a warming climate should consider the effects on microclimate buffering that accompany changes to forest structure aimed at increasing understory light (De Frenne et al., 2021; Sanczuk et al., 2023). Based on our year-round models of understory buffering, the riskiness of increasing understory stress seems highest in late spring and mid-summer. Given the role of forest management in shaping understory microclimates, silvicultural strategies that include full overstory removal should consider the potential for increasing the *rate* of warming in the understory relative to macroclimate warming (Zellweger et al., 2020), as existing understory vegetation in these stands could go from being highly buffered to unbuffered in the short span of time that it takes to complete an overstory removal. At the same time, forest management operations can leverage the buffering effect of forest canopies to manage for climate refugia through the strategic maintenance of highly buffered zones (Díaz-Calafat et al., 2023; Pradhan et al., 2023). Therefore, considering the impacts to microclimate accompanied by changes in forest structure widens the purview of forest management planning aimed at promoting adaptation and resilience to climate change.

CHAPTER 3: FOREST COVER BUFFERS MICROCLIMATE AND INCREASES FUEL MOISTURE IN NORTHERN CONIFER FORESTS

3.1 Introduction

Monitoring and predicting conditions that contribute to fire spread are central to the National Fire Danger Rating System (NFDRS) as well as fire management planning that relies on these danger ratings (Holden & Jolly, 2011; Schroeder & Buck, 1983). Both the NFDRS and management operations use fire behavior models that consider how weather, fuels, and topography may interact to create potential fire behavior for a given area (Cohen & Deeming, 1985; Rothermel, 1983). Most fire behavior models assume weather and dead fuel moisture to be spatially uniform over a given area of interest (Andrews, 2014; Pinto & Fernandes, 2014). However, in forested systems fine scale variation in stand structure may lead to highly heterogeneous microclimate (i.e., temperature and moisture) and fuel moisture conditions in the understory where fires often ignite and spread (Kane, 2021; Loudermilk et al., 2012; Pickering et al., 2021). Therefore, in order to support fire management decision making by improving predictions of fire behavior in forested landscapes, we must increase our understanding of how forest structure affects understory microclimate and fuel moisture.

Tree canopies can buffer understories from broader macroclimate conditions that occur outside of forests (De Frenne et al., 2019; De Lombaerde et al., 2022; Geiger et al., 2012). This buffering effect is largely driven by canopy leaves and branches absorbing solar radiation that would otherwise penetrate the forest floor, which can lead to open areas being warmer and less humid than closed canopy areas (De Frenne et al., 2021; Pickering et al., 2021). Forest structure has also been shown to impact dead fuel moisture in mesic systems, where dense cover tends to produce higher fuel moisture (Barberá et al., 2023; Cawson et al., 2017; Tanskanen et al., 2006). However, studies from arid climates have reported limited effects of forest structure on dead fuel moisture (Estes et al., 2012; Faiella & Bailey, 2007). The different relationships between forest structure and dead fuel moisture across forest types highlights the importance of ecological context when assessing fuel availability for burning, which relies on both the moisture and loading of fuels (Rothermel, 1983; Schroeder & Buck, 1983). For example, while dense forests can have high loading of dead surface fuels from woody debris accumulation (Agee, 1996; Van De Water & North, 2011), forest cover may also cause increased fuel moisture in those stands thereby reducing fuel availability (Barberá et al., 2023; De

Frenne et al., 2021; Walker, 2020). Therefore, more research is needed about how forest structure impacts understory fuel availability by moderating microclimate and dead fuel moisture, especially in systems where fire research is limited such as the northeastern USA.

Forest management operations that alter stand structure through prescribed burning or mechanical harvesting can create profound secondary effects on understory microclimate and dead fuel moisture (Aussenac, 2000; Whitehead et al., 2006). Moreover, such changes to forest structure can also shape plant regeneration in ways that influence long-term feedbacks between community composition, vegetation structure, and abiotic conditions in the understory (Loudermilk et al., 2022; Mitchell et al., 2009; Zellweger et al., 2020). Despite the strong influence of within-stand structural variation on biotic and abiotic forest conditions, quantifying forest structure at fine spatial scales (sub-plot level) is challenging with traditional forest inventory methods (Loudermilk et al., 2012; Parsons et al., 2011; White et al., 2013). Terrestrial laser scanning (TLS) is an emerging technology that can address this issue by using light detection and ranging (lidar) to generate forest structure quantifications that capture more variability than traditional methods (Gallagher et al., 2021; Loudermilk et al., 2012; Maxwell et al., 2023). Therefore, using emerging technologies to disentangle the complex interactions between forest structure, microclimate, and fuel moisture can improve fire management planning across temporal scales by refining fire behavior modeling in the short term as well as enhancing predictions of long-term forest ecosystem dynamics (Kane, 2021; Loudermilk et al., 2022; Mitchell et al., 2009; Zellweger et al., 2020).

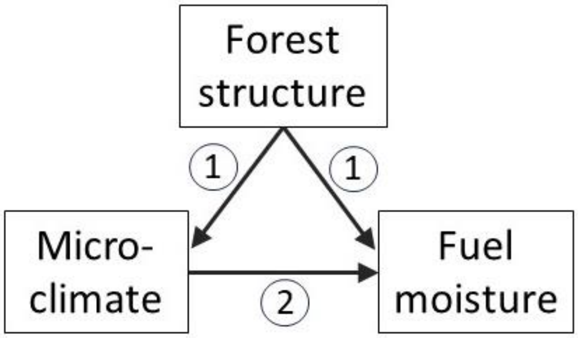


Figure 3.1. Conceptual depiction of study objectives. Objective 1: determine the extent to which forest structure can predict microclimate and fuel moisture across a diverse range of managed stands. Objective 2: evaluate the effectiveness of microclimate measurements for predicting fuel moisture in northeastern fuel types.

In this study, we use a combination of field-based climate data loggers, fuel moisture analyses, TLS, and traditional forest inventory measurements to support fire and fuels management in northern conifer forests by better understanding the relationships between forest structure, microclimate, and fuel moisture.

We address this goal by pursuing two research objectives: 1) determine the extent to which forest structure impacts microclimate and fuel moisture across a diverse range of managed stands; and 2) evaluate the effectiveness of microclimate measurements for predicting fuel moisture in northeastern fuel types (Figure 3.1). This research enhances fire managers' ability to plan and implement fuel treatments by highlighting how changes in forest stand structure drive fine scale heterogeneity in fuel availability.

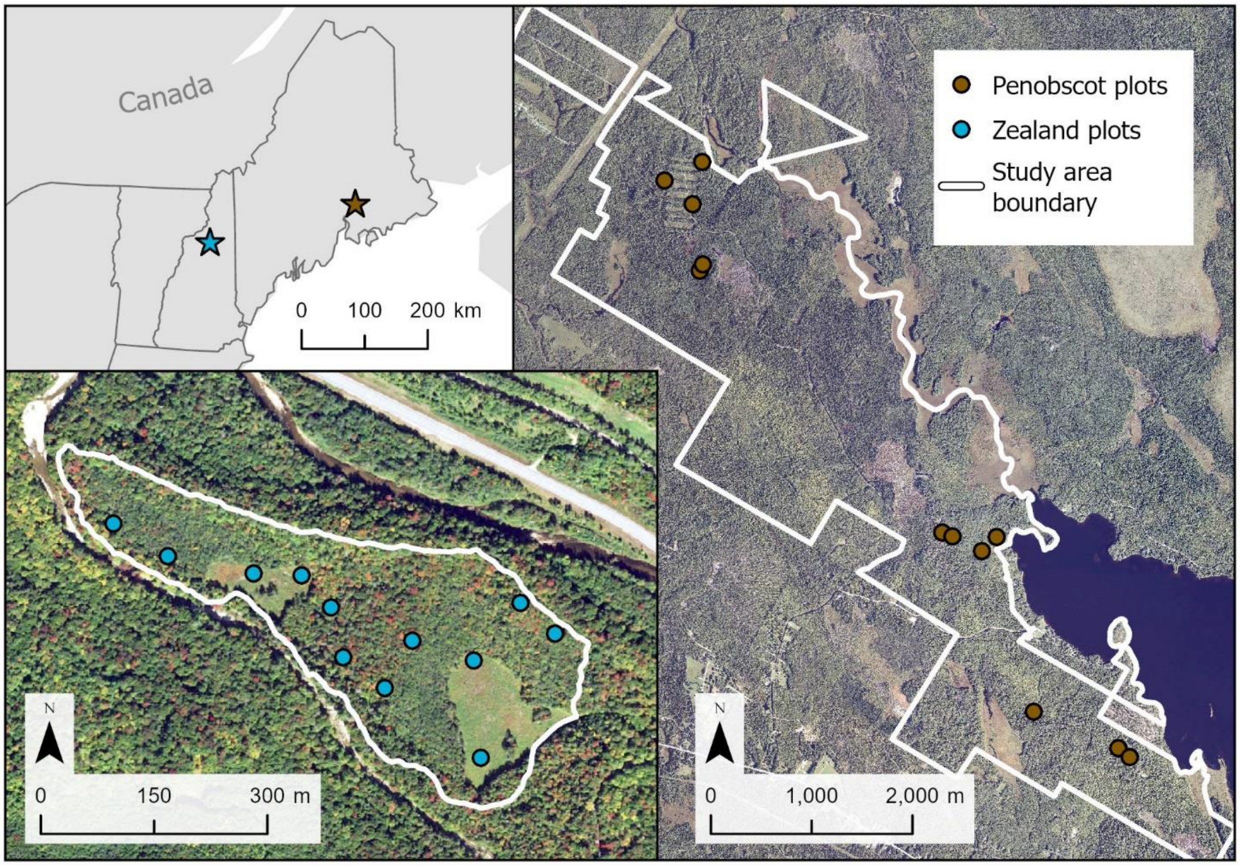


Figure 3.2. Study area map showing the Penobscot Experimental Forest (right) and Zealand (bottom left), as well as their respective locations in Maine and New Hampshire in the northeast U.S. (top left). Colored points depict 24 study plots (12 at each study location) established across a broad range of forest structures. Each plot included a 10-meter fixed radius forest inventory with a microclimate sensor and fuel moisture array located at plot center (See Figure C.1).

3.2 Methods

3.2.1 Study areas and site selection

This study focused on two areas in the northeastern USA: the Penobscot Experimental Forest (PEF) in central Maine and Zealand (ZEL) in northern New Hampshire (Figure 3.2) that provide a broad range of canopy structures and compositions. The PEF is a long-term silvicultural research forest managed by the USDA Forest

Service Northern Research Station. The PEF contains over 50 individual management units that have received a range of experimental harvesting treatments, from high basal area removal (i.e., commercial clearcut) to low basal area removal (i.e., single tree selection), as well as intermediate treatments (i.e., thinning). Additionally, stand-level species compositions range from pure evergreen needle-leaved to pure deciduous broadleaved, with many mixed stands interspersed. Common species include red spruce (*Picea rubens*), balsam fir (*Abies balsamea*), northern white cedar (*Thuja occidentalis*), eastern white pine (*Pinus strobus*), eastern hemlock (*Tsuga canadensis*), red maple (*Acer rubrum*), northern red oak (*Quercus rubra*), paper birch (*Betula papyrifera*), bigtooth aspen (*Populus grandidentata*), and American beech (*Fagus grandifolia*). The elevation at the PEF ranges from 8 to 80 meters above sea level.

ZEL is part of the White Mountain National Forest, which is managed by the USDA Forest Service. ZEL is actively managed for recreational trails and wildlife habitat, with approximately 14% of the area maintained as early successional habitat (DeGraaf et al., 2006) through prescribed burning and mowing. The remainder of ZEL is dominated by semi-closed canopy and closed canopy forest, with common species including white spruce (*Picea glauca*), red spruce (*Picea rubens*), balsam fir (*Abies balsamea*), eastern white pine (*Pinus strobus*), black cherry (*Prunus* serotina), red maple (*Acer rubrum*), bigtooth aspen (*Populus grandidentata*), sugar maple (*Acer saccharum*), paper birch (*Betula papyrifera*), and American beech (*Fagus grandifolia*). The elevation at ZEL ranges from 400 to 450 meters above sea level.

Since canopy openness is suggested to be a major driver of microclimate and fuel moisture (Brown et al., 2022; De Frenne et al., 2019), we established 24 study sites (12 at PEF and 12 at ZEL) that captured a broad range of canopy structures, from fully open to fully closed canopies. To do this, we used satellite imagery and field visits to identify potential sampling zones that we separated into three strata of canopy openness (i.e., open, intermediate, and closed). Additional criteria for sampling zones included that they must be at least 30 meters from a major gravel road and at least 30 meters from a major water body. Once we identified potential sampling zones at each location (7 in each canopy stratum at PEF-21 total; 6 in each canopy stratum at ZEL-18 total), we conducted a stratified random sampling to determine site locations. First, we randomly selected a zone from a stratum, then used a 5-meter gridded overlay (based on functional accuracy of handheld GPS) to randomly select a location within the zone. Once a location was randomly selected, we ground-validated the location to ensure that: 1) it met the canopy stratum requirements (i.e., greater than 66% canopy openness for open sites; 33-66% canopy openness for intermediate sites; less than 33% canopy openness for closed sites); 2) it had no evidence of standing water (i.e., not a forested wetland); and 3) it was at least 50 meters from a previously selected site. If any of these criteria were not met, we repeated the selection process within the selected zone until all criteria were met. At each site we then established a 10-meter fixed radius forest plot in which we would conduct all measurements for the study.

3.2.2 Microclimate data

To quantify microclimate conditions at each site, we measured air temperature and relative humidity every hour using iButton data loggers (Hygrochron model DS1923, resolution 0.5 °C and 0.6% RH; Maxim Integrated Products, Inc., Sunnyvale, California). To minimize exposure to solar radiation and precipitation while allowing for adequate air mixing, each iButton logger was suspended inside a vented radiation shield with additional overhead radiation cover (modified from Wason et al., 2017) and fastened to a wooden post one meter above the ground (pictured in Figure C.1). Posts were placed in the center of each site and oriented so that radiation shields were on the south side of the stake. Sensors remained in the field from July 2023 to December 2023. All microclimate time series data were inspected prior to data analysis. Our final dataset included hourly measurements of temperature and relative humidity from July 7, 2023 to September 5, 2023.

3.2.3 Fuel moisture data

To quantify fuel moisture content (FMC) at each site, we placed 10-hour fuel stick arrays directly below the microclimate sensor (Figure C.1) in late June and early July. Fuel stick arrays consisted of four rectangular (2cm x 2cm x 36cm) pieces of jack pine (*Pinus banksiana*) fastened to a plastic frame (Figure C.1). Prior to placing them in the field, we oven dried the fuel sticks at 100 °C until they reached constant mass (>120 hours) and immediately weighed them on an electronic balance to measure their dry weights (range 52.02-73.30 grams). Once in the field, we measured the field mass of the sticks twice at each site during the study period, once at two days since rain (DSR) and once at 6 days DSR, using the same electronic balance that we used to measure the dry mass. FMC (%) was calculated as 100 times the difference between the field mass and the dry mass divided by the dry mass.

3.2.4 Traditional forest inventory data

To acquire traditional forest structure and composition measurements at each site, we conducted fixed-radius, nested plot surveys (10-meter outer radius; 6-meter nest radius) in August 2023. We recorded diameter at breast height (DBH) and species of all trees greater than 11 centimeters DBH within each outer plot, and all trees greater than 1 centimeter DBH within each nested plot. For each site, we calculated total basal area, trees per acre, and evergreen cover basal area (Table C.1). We also calculated canopy openness at each site by computing the mean of four measurements taken in cardinal directions with a spherical densiometer (Forestry Suppliers Spherical Crown Densiometer, Convex Model A; see Beeles et al., 2022) held directly over each iButton logger (Figure C.1).

3.2.5 Terrestrial laser scanning data

To estimate forest structure from terrestrial laser scanning (TLS), we scanned each plot with a BLK360 TLS (Leica Geosystems, Heerbrugg, Switzerland) in August 2023. The TLS unit operated from a tripod at plot center that was tall enough to be placed over the microclimate and fuel moisture array so that they were not captured in the scan. For each plot, the unit collected a 360° panoramic RGB image followed by a full *360°* spherical lidar scan to produce a three-dimensional point cloud. We clipped all point clouds to a 10-meter radius in order to match traditional inventory plots. Next, we classified points into ground and non-ground which were further used to produce a digital terrain model (DTM) and normalized point cloud. We used the normalized point cloud to generate height and intensity metrics (Roussel et al., 2020), as well as a suite of custom metrics as described in Gallagher et al., 2021 and Maxwell et al., 2023 *(*Table C.2*).*

3.2.6 Data analyses

For each site, we calculated daily values of maximum temperature (T_{max}; Figure 3.3a shows mean of all sites at each location) and minimum relative humidity (RH_{min}; Figure 3.3b shows mean of all sites at each location), as well as mean values of T_{max} and RH_{min} for the entire study period (Table C.3). For each round of fuel moisture measurements at each site, we calculated site-level means of FMC from the four sticks in each array.

To determine how microclimate buffering was driven by traditional forest structure metrics (Objective 1), we built a set of linear mixed effects models (LMMs) predicting mean values of T_{max} and RH_{min} for the entire study period as a function of canopy openness, basal area, and trees per acre. We included a random effect

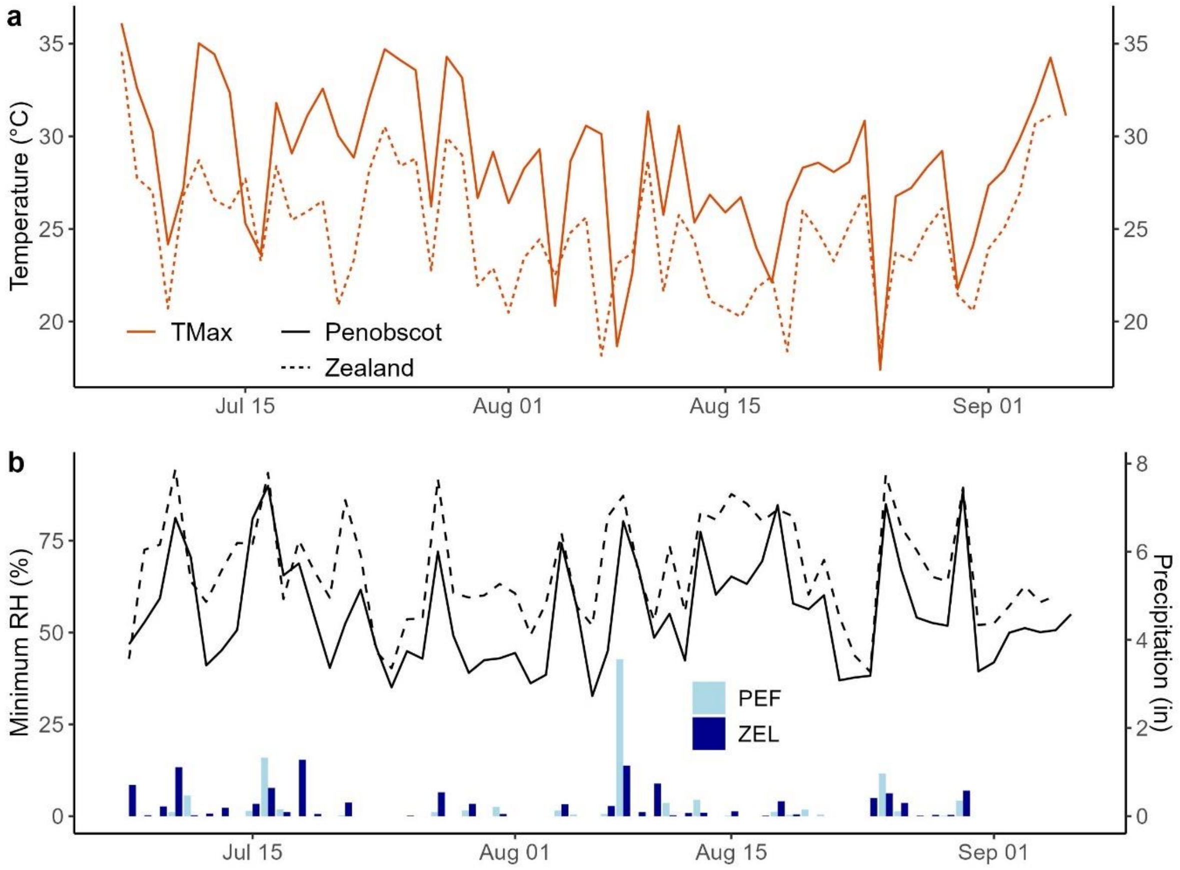


Figure 3.3. Site-level microclimate summaries. a) Daily values of maximum air temperature (T_{max}) and **b)** minimum relative humidity (RH_{min}) averaged across all plots at each study location. Precipitation totals from the nearest National Weather Service station to the Penobscot (PNB) and Zealand (ZLD) are show on the bottom of panel b.

for study location (i.e., PEF vs. ZEL) to account for the locations having significantly different climates during the study period (Table C.3). We built models with all possible combinations of predictors (but no interactions), then ranked the models based on values of corrected Akaike Information Criterion (AICc) and selected only the models that were within 10 ΔAICc of the best model. We assessed performance by taking the mean conditional R^2 (R^2_c), marginal R^2 (R^2_m), and root mean square error (RMSE) of all the top models. To compare model performance across response variables with different units (T_{max} and RH_{min}) we used normalized root mean square error (nRMSE), which is a measure of model error that is standardized by the mean of the response variable.

To determine how fuel moisture could be predicted by traditional forest structure metrics (Objective 1), we use the same approach as above to build a set of LMMs predicting FMC as a function of canopy openness, basal area, and trees per acre. To account for dead fuel moisture being impacted by recent precipitation, we included a random effect for days since rain (DSR) nested within study location. We used the same AICc selection process as above to rank and choose model predictors (Table C.6).

When building LMMs to predict FMC from microclimate variables (Objective 2), we also accounted for dead fuel moisture being impacted by recent weather conditions. We first calculated means of T_{max} and RH_{min} for the five days prior to each round of fuel moisture measurements, which were then used to predict the corresponding FMC values. We also included a random effect for days since rain (DSR) nested within study location.

Due to the large number of TLS metrics (>200) relative to the number of sites (24) for predicting FMC, we conducted a variable selection process using random forests (VSURF; vsurf package in R) to identify important TLS variables to include in our models (Objective 1). From the VSURF process, two variables emerged as being important for predicting FMC: per_gap (percent of returns occurring in gaps) and s_l5_prop_sd (standard deviation of the proportion of returns occurring above 2-meter height). Once these variables were identified, we carried out the same AICc selection process to rank and choose the top LMMs. To determine if TLS can predict traditional forest inventory metrics, we first used

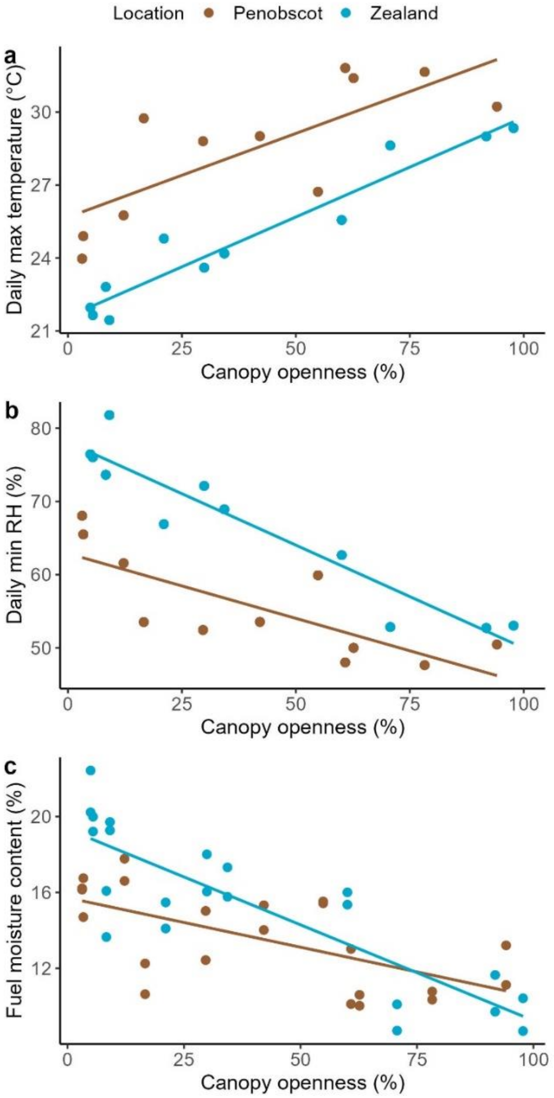


Figure 3.4. Scatterplots of microclimate and fuel moisture variables as a function of canopy openness. a) Daily maximum temperature (T_{max}), **b)** daily minimum relative humidity (RH_{min}), and **c)** fuel moisture content (FMC) as a function of canopy openness measured with a spherical densiometer at the center of each plot. Lines represent separate simple linear regressions for each site for visualization. However, we used linear mixed effects models to test these effects and found that canopy openness was a significant predictor of all three variables and there were either significant main effects of site (a and b) or an interaction with site (c; see results text).

VSURF to identify important variables for modeling canopy openness, basal area, and trees per acre as response variables. Once TLS variables were identified, we ran linear models and used values of R^2 and RMSE to assess performance.

3.3 Results

We found that forest structure strongly affects understory microclimate, with open canopy sites being significantly warmer (mean T_{max} difference of 7.87 °C) and drier (mean RH_{min} difference of 24.73%) than closed canopy sites (Figure 3.4a, 4b). We also found that open canopy sites had significantly drier fuels (mean FMC difference of 9.66%) than closed canopy sites (Figure 3.4c). Interestingly, the relationships between canopy openness and microclimate were consistent across our two study locations (non-significant interaction

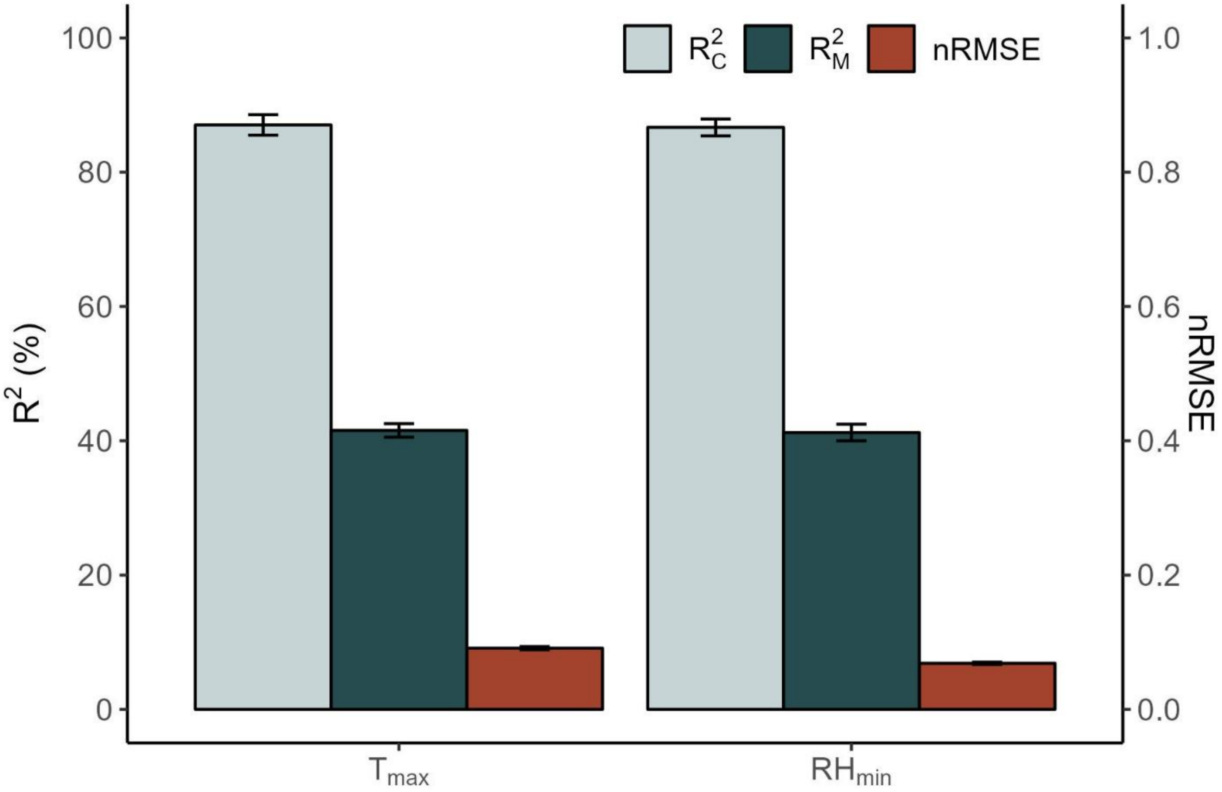


Figure 3.5. Performance from linear mixed models (LMMs) predicting mean daily maximum temperature (T_{max}) and mean daily minimum relative humidity (RH_{min}) from estimates of canopy openness, basal area, and trees per acre measured at each plot. Error bars depict one standard error. For each response variable, we ran all LMMs within 10 ΔAIC of the top model (n = 3 for each response variable), and the figure shows the mean output of these models. All models included a random effect for study location. Conditional R^2 (R^2_c) depicts the total variation explained by fixed and random effects, while marginal R^2 (R^2_m) depicts the variation explained by fixed effects. nRMSE is normalized root mean square error, which is a measure of model error that is standardized across response variable units.

between canopy openness and location), despite the PEF being generally warmer and less humid over the study period (Figure 3.4a, 4b; Table C.3). On the other hand, decline in FMC was stronger (more negative) with increasing canopy openness at ZEL compared to the PEF (significant interaction p-value 0.021; Figure 3.4c).

Our models predicting microclimate from traditional forest inventory metrics consistently explained over 85% of the variation in daily averages of T_{max} (mean R^2_c of 0.86) and RH_{min} (mean R^2_c of 0.87) (Figure 3.5). On average, the fixed effects of forest structure (i.e., canopy openness, basal area, and trees per acre) explained 41% of the variation (R^2_m) in T_{max} and RH_{min}, while the random effect for study location explained 45% of the variation in T_{max} and RH_{min} (Figure 3.5). Canopy openness occurred in two of the three top models from our AIC selection process, and when plotted in bivariate relationships with microclimate variables it explained 54% of variation in T_{max} and 55% of variation in RH_{min} (Figure 3.4a, 4b). However, basal area and trees per acre were also prominent predictors, due to high collinearity between forest structure metrics (Figure C.2). We found that TLS metrics were generally able to predict canopy openness, basal area, and trees per acre (Figure 3.6), as well as T_{max} and RH_{min} (Figure C.3).

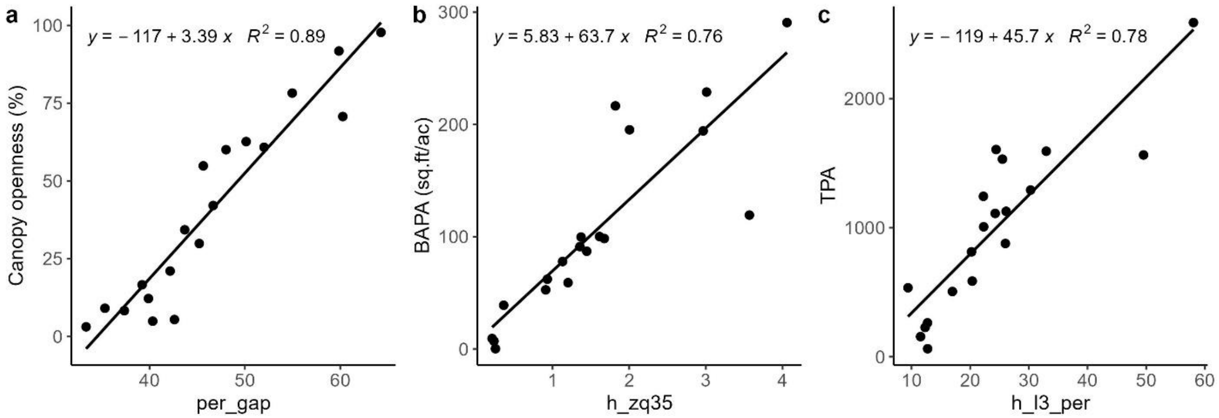


Figure 3.6. Bivariate relationships between terrestrial laser scanning (TLS) and traditional inventory variables. Each panel shows the top TLS-derived individual predictors of **a)** canopy openness, **b)** basal area (BAPA), and **c)** trees per acre (TPA). See Table C.2 for variable descriptions.

We found microclimate variables to be better predictors of FMC (mean R^2_c of 0.88) than forest structure variables regardless of if they were measured by TLS (mean R^2_c of 0.74) or traditional forest inventory (mean R^2_c of 0.64; Figures 7 and 8). On average, the fixed effects of microclimate or forest structure

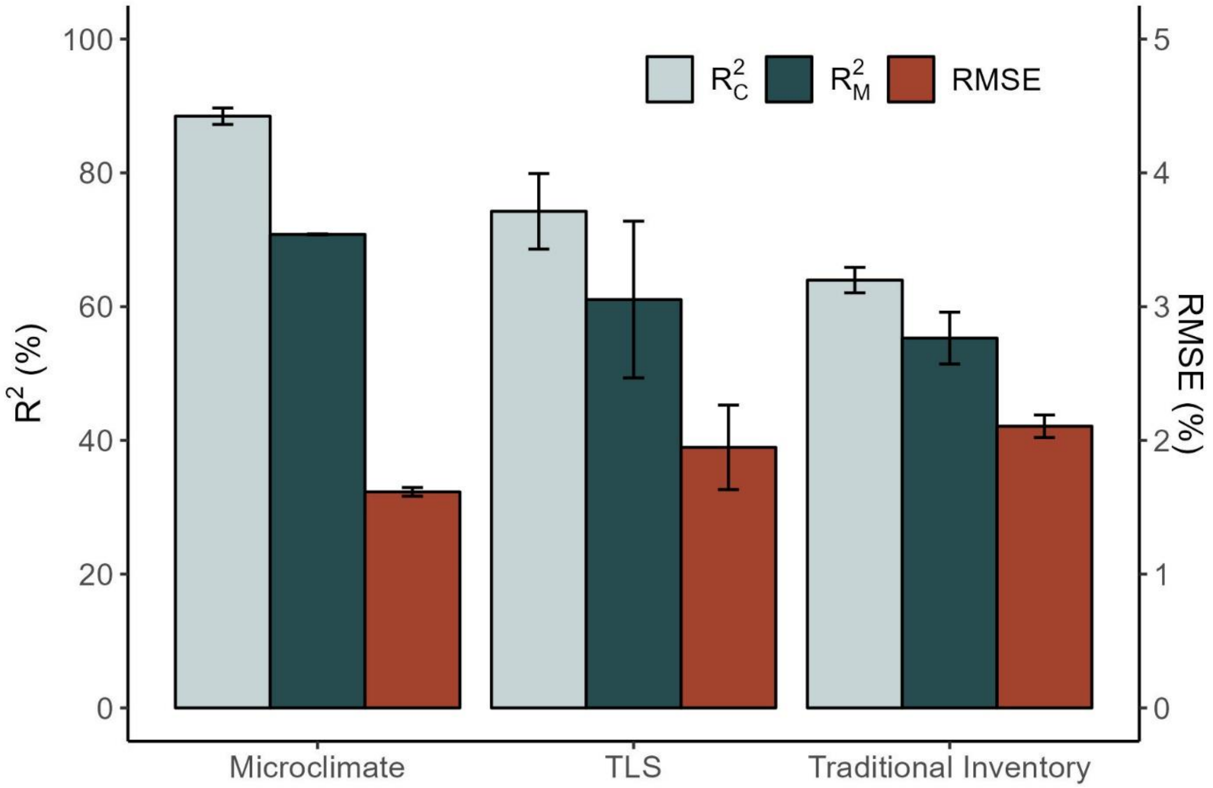


Figure 3.7. Performance from linear mixed models (LMMs) predicting fuel moisture content (FMC) from variables derived from microclimate, terrestrial laser scanning (TLS), or traditional forest inventory measurements. Error bars depict one standard error. For each set of predictor variables, we ran all LMMs within 10 ΔAIC of the top model (n = 2-5 depending on predictor variables), and the figure shows the mean output of these models. All models included a random effect for days since rain (DSR) nested within study location. Conditional R^2 (R^2_c) depicts the total variation explained by fixed and random effects, while marginal R^2 (R^2_m) depicts the variation explained by fixed effects. Root mean square error (RMSE) is a measure of model error.

explained the majority of the variation in FMC (mean R^2_m of 0.62), while the random effects for days since rain (DSR) and study location on average explained 13% of the variation in FMC (Figure 3.7). When plotting microclimate variables in bivariate relationships with FMC, we found that T_{max} explained the most variation in FMC ($R^2 = 0.71$; Figure 3.8a), with RH_{min} ($R^2 = 0.63$) being a close second which is likely due to high collinearity between the two variables (Figure C.2). When plotting TLS variables in bivariate relationship with FMC, we found that per_gap (percent of returns occurring in gaps) explained the most variation in FMC ($R^2 = 0.53$; Figure 3.8b). Finally, when plotting traditional forest inventory metrics in bivariate relationships with FMC, we found that canopy openness explained the most variation in FMC ($R^2 = 0.55$; Figure 3.8c).

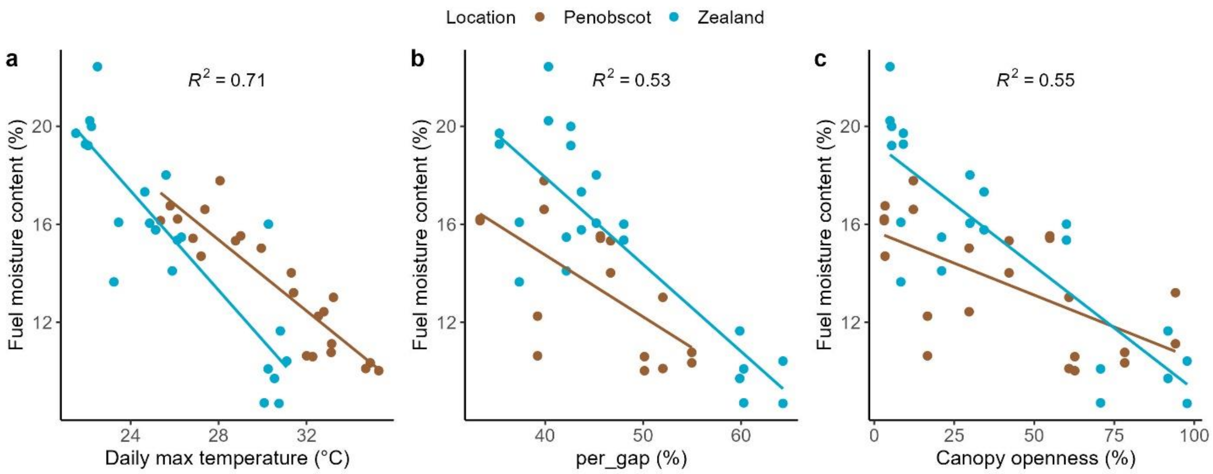


Figure 3.8. Bivariate relationships of the top individual predictors of fuel moisture content (FMC) from **a)** microclimate variables, **b)** terrestrial laser scanning (TLS) variables, and **c)** ground-based forest structure variables. Lines represent separate simple linear regressions for each location, while R^2 values in each panel correspond to the overall relationship not accounting for site location.

3.4 Discussion

Our findings support other research from mesic systems demonstrating that dense forest cover reduces fuel availability by buffering microclimate (De Frenne et al., 2019; De Lombaerde et al., 2022) and increasing dead fuel moisture (Barberá et al., 2023; Cawson et al., 2017; Tanskanen et al., 2006). This also supports other research of forest structure interacting with the fire environment in ways beyond that of just being fuel (Loudermilk et al., 2022; Mitchell et al., 2009). We found that canopy openness is the main structural driver of these effects on understory conditions (von Arx et al., 2013); however, basal area and trees per acre metrics were also good predictors due to high collinearity between variables. The strong influence of forest structure on understory microclimate and dead fuel moisture is further supported by our models that used TLS-derived variables as predictors. In fact, TLS-derived variables were better predictors of dead fuel moisture than traditional forest inventory metrics, presumably due to the ability of TLS to quantify fine scale structural variation that is not captured in traditional inventories (Gallagher et al., 2021; Loudermilk et al., 2012; Parsons et al., 2011). Therefore, we recommend that fuels management operations consider the effect of canopy buffering on understory microclimate and dead fuel moisture, and our results support the use of TLS for monitoring stand structure.

Our findings regarding the effect of forest cover on understory conditions can help fire managers design thinning prescriptions that seek to achieve a certain level of understory microclimate and dead fuel moisture. In fire-excluded systems that have been colonized by fire-intolerant plant species (i.e. mesophication), mechanical thinning is often needed prior to prescribed burning for instances where managers way want to restore fire-adapted ecosystems. Our results can aid in identifying target stand conditions that may produce desirable understory microclimates for conducting fire operations. For fire protection operations that seek to limit fire spread, our results support the use of shaded fuel breaks (also called green fuel breaks), which reduce overall fuel availability by decreasing understory fuel loads while maintaining a semi-closed canopy in order to retain some level of buffering for microclimate and dead fuel moisture (Agee et al., 2000; St. John & Ogle, 2009). Therefore, the relationships between forest structure and understory conditions can be used to fine tune a wide variety of targets related to fire and fuels management.

Our results support the underlying theory of models that predict dead fuel moisture from weather conditions (Cohen & Deeming, 1985; Rothermel, 1983) by demonstrating that microclimate variables were better predictors of dead fuel moisture than forest structure variables. However, we also found that microclimate and fuel moisture can vary drastically within the same stand, depending on the density of overlying forest cover in any particular location (Geiger et al., 2012; Tanskanen et al., 2006; Zellweger et al., 2020). Therefore, the accuracy of models predicting landscape-level dead fuel moisture could be improved by incorporating adjustments for forest cover at management-relevant scales (Tanskanen et al., 2006). Given the ease, efficiency, and effectiveness of using TLS to estimate forest structure, our results support the use of this emerging technology for refining landscape-level models of microclimate and dead fuel moisture to improve fire danger calculations and fire risk assessments.

BIBLIOGRAPHY

Acharya, R. P., Maraseni, T., & Cockfield, G. (2019). Global trend of forest ecosystem services valuation – An analysis of publications. *Ecosystem Services*, *39*, 100979. https://doi.org/10.1016/j.ecoser.2019.100979

Agee, J. K. (1996). The Influence of Forest Structure on Fire Behavior. *Proceedings from the 17th Forest Vegetation Management Conference*.

Agee, J. K., Bahro, B., Finney, M. A., Omi, P. N., Sapsis, D. B., Skinner, C. N., van Wagtendonk, J. W., & Weatherspoon, C. P. (2000). The use of shaded fuelbreaks in landscape fire management. *Forest Ecology and Management*.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S. W., Semerci, A., & Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, 26.

Ambrose-Oji, B., Atkinson, M., Petrokofsky, G., & Hemery, G. (2020). Do Environmental Worldviews and Distrust Influence Action for Adaptation to Environmental Change Among Small-Scale Woodland Managers? *Small-Scale Forestry*, *19*(2), 159–185. https://doi.org/10.1007/s11842-020-09440-x

Andersson, E., Keskitalo, E., & Lawrence, A. (2017). Adaptation to Climate Change in Forestry: A Perspective on Forest Ownership and Adaptation Responses. *Forests*, *8*(12), 493. https://doi.org/10.3390/f8120493

Andrews, P. L. (2014). Current status and future needs of the BehavePlus Fire Modeling System. *International Journal of Wildland Fire*, *23*(1), 21. https://doi.org/10.1071/WF12167

Aussenac, G. (2000). Interactions between forest stands and microclimate: Ecophysiological aspects and consequences for silviculture. *Annals of Forest Science*, *57*(3), 287–301. https://doi.org/10.1051/forest:2000119

Ayrey, E., Hayes, D. J., Fraver, S., Kershaw, J. A., & Weiskittel, A. R. (2019). Ecologically-Based Metrics for Assessing Structure in Developing Area-Based, Enhanced Forest Inventories from LiDAR. *Canadian Journal of Remote Sensing*, *45*(1), 88–112. https://doi.org/10.1080/07038992.2019.1612738

Barberá, I., Paritsis, J., Ammassari, L., Morales, J. M., & Kitzberger, T. (2023). Microclimate and species composition shape the contribution of fuel moisture to positive fire-vegetation feedbacks. *Agricultural and Forest Meteorology*, *330*, 109289. https://doi.org/10.1016/j.agrformet.2022.109289

Beeles, K. L., Tourville, J. C., & Dovciak, M. (2022). Characterizing Canopy Openness Across Large Forested Landscapes Using Spherical Densiometer and Smartphone Hemispherical Photography. *Journal of Forestry*, *120*(1), 37–50. https://doi.org/10.1093/jofore/fvab046

Bhattarai, R., Rahimzadeh-Bajgiran, P., Weiskittel, A., Homayouni, S., Gara, T. W., & Hanavan, R. P. (2022). Estimating species-specific leaf area index and basal area using optical and SAR remote sensing data in Acadian mixed spruce-fir forests, USA. *International Journal of Applied Earth Observation and Geoinformation*, *108*, 102727. https://doi.org/10.1016/j.jag.2022.102727

Bissonnette, J.-F., Dupras, J., Doyon, F., Chion, C., & Tardif, J. (2017). Perceptions of Small Private Forest Owner's Vulnerability and Adaptive Capacity to Environmental Disturbances and Climate Change: Views from a Heterogeneous Population in Southern Quebec, Canada. *Small-Scale Forestry*, *16*(3), 367–393. https://doi.org/10.1007/s11842-016-9361-y

Blennow, K., Persson, J., Tomé, M., & Hanewinkel, M. (2012). Climate Change: Believing and Seeing Implies Adapting. *PLoS ONE*, *7*(11), e50182. https://doi.org/10.1371/journal.pone.0050182

Boag, A. E., Hartter, J., Hamilton, L. C., Christoffersen, N. D., Stevens, F. R., Palace, M. W., & Ducey, M. J. (2018). Climate change beliefs and forest management in eastern Oregon: Implications for individual adaptive capacity. *Ecology and Society*, *23*(4), art1. https://doi.org/10.5751/ES-10355-230401

Brown, T. P., Inbar, A., Duff, T. J., Lane, P. N. J., & Sheridan, G. J. (2022). The sensitivity of fuel moisture to forest structure effects on microclimate. *Agricultural and Forest Meteorology*, *316*, 108857. https://doi.org/10.1016/j.agrformet.2022.108857

Butler, B. J. (2018). *Family Forest Ownerships of the United States, 2018: Results from the USDA Forest Service, National Woodland Owner Survey*. 57.

Butler, B. J., & Butler, S. M. (2016). *Family Forest Ownerships with 10+ Acres in Maine, 2011-2013* (NRS-RN-219; p. NRS-RN-219). U.S. Department of Agriculture, Forest Service, Northern Research Station. https://doi.org/10.2737/NRS-RN-219

Butler, B. J., Tyrrell, M., Feinberg, G., VanManen, S., Wiseman, L., & Wallinger, S. (2007). Understanding and Reaching Family Forest Owners: Lessons from Social Marketing Research. *Journal of Forestry*, 10.

Carter, D. R., Seymour, R. S., Fraver, S., & Weiskittel, A. (2017). Reserve tree mortality in two expanding-gap silvicultural systems 20 years after establishment in the Acadian forest of Maine, USA. *Forest Ecology and Management*, *389*, 149–157. https://doi.org/10.1016/j.foreco.2016.12.031

Cawson, J. G., Duff, T. J., Tolhurst, K. G., Baillie, C. C., & Penman, T. D. (2017). Fuel moisture in Mountain Ash forests with contrasting fire histories. *Forest Ecology and Management*, *400*, 568–577. https://doi.org/10.1016/j.foreco.2017.06.046

Charnley, S., Diaz, D., & Gosnell, H. (2010). Mitigating Climate Change Through Small-Scale Forestry in the USA: Opportunities and Challenges. *Small-Scale Forestry*, *9*(4), 445–462. https://doi.org/10.1007/s11842-010-9135-x

Chen, J., Saunders, S. C., Crow, T. R., Naiman, R. J., Brosofske, K. D., Mroz, G. D., Brookshire, B. L., & Franklin, J. F. (1999). Microclimate in Forest Ecosystem and Landscape Ecology. *BioScience*, *49*(4), 288–297.

Cohen, J. D., & Deeming, J. E. (1985). *The national fire-danger rating system: Basic equations* (PSW-GTR-82; p. PSW-GTR-82). U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. https://doi.org/10.2737/PSW-GTR-82

Cook, B., Corp, L., Nelson, R., Middleton, E., Morton, D., McCorkel, J., Masek, J., Ranson, K., Ly, V., & Montesano, P. (2013). NASA Goddard's LiDAR, Hyperspectral and Thermal (G-LiHT) Airborne Imager. *Remote Sensing*, *5*(8), 4045–4066. https://doi.org/10.3390/rs5084045

De Frenne, P., Lenoir, J., Luoto, M., Scheffers, B. R., Zellweger, F., Aalto, J., Ashcroft, M. B., Christiansen, D. M., Decocq, G., De Pauw, K., Govaert, S., Greiser, C., Gril, E., Hampe, A., Jucker, T., Klinges, D. H., Koelemeijer, I. A., Lembrechts, J. J., Marrec, R., … Hylander, K. (2021). Forest microclimates and climate change: Importance, drivers and future research agenda. *Global Change Biology*, *27*(11), 2279–2297. https://doi.org/10.1111/gcb.15569

De Frenne, P., Zellweger, F., Rodríguez-Sánchez, F., Scheffers, B. R., Hylander, K., Luoto, M., Vellend, M., Verheyen, K., & Lenoir, J. (2019). Global buffering of temperatures under forest canopies. *Nature Ecology & Evolution*, *3*(5), 744–749. https://doi.org/10.1038/s41559-019-0842-1

De Lombaerde, E., Vangansbeke, P., Lenoir, J., Van Meerbeek, K., Lembrechts, J., Rodríguez-Sánchez, F., Luoto, M., Scheffers, B., Haesen, S., Aalto, J., Christiansen, D. M., De Pauw, K., Depauw, L., Govaert, S., Greiser, C., Hampe, A., Hylander, K., Klinges, D., Koelemeijer, I., … De Frenne, P. (2022). Maintaining forest cover to enhance temperature buffering under future climate change. *Science of The Total Environment*, *810*, 151338. https://doi.org/10.1016/j.scitotenv.2021.151338

De Pauw, K., Sanczuk, P., Meeussen, C., Depauw, L., De Lombaerde, E., Govaert, S., Vanneste, T., Brunet, J., Cousins, S. A. O., Gasperini, C., Hedwall, P., Iacopetti, G., Lenoir, J., Plue, J., Selvi, F., Spicher, F., Uria-Diez, J., Verheyen, K., Vangansbeke, P., & De Frenne, P. (2022). Forest understorey communities respond strongly to light in interaction with forest structure, but not to microclimate warming. *New Phytologist*, *233*(1), 219–235. https://doi.org/10.1111/nph.17803

DeGraaf, R. M., Yamasaki, M., Leak, W. B., & Lester, A. M. (2006). *Technical Guide to Forest Wildlife Habitat Management in New England*. Burlington, VT: University of Vermont Press, and Hanover, NH: University Press of New England.

Díaz-Calafat, J., Uria-Diez, J., Brunet, J., De Frenne, P., Vangansbeke, P., Felton, A., Öckinger, E., Cousins, S. A. O., Bauhus, J., Ponette, Q., & Hedwall, P.-O. (2023). From broadleaves to conifers: The effect of tree composition and density on understory microclimate across latitudes. *Agricultural and Forest Meteorology*, *341*, 109684. https://doi.org/10.1016/j.agrformet.2023.109684

Ehbrecht, M., Schall, P., Ammer, C., Fischer, M., & Seidel, D. (2019). Effects of structural heterogeneity on the diurnal temperature range in temperate forest ecosystems. *Forest Ecology and Management*, *432*, 860–867. https://doi.org/10.1016/j.foreco.2018.10.008

Ehbrecht, M., Schall, P., Ammer, C., & Seidel, D. (2017). Quantifying stand structural complexity and its relationship with forest management, tree species diversity and microclimate. *Agricultural and Forest Meteorology*, *242*, 1–9. https://doi.org/10.1016/j.agrformet.2017.04.012

Estes, B. L., Knapp, E. E., Skinner, C. N., & Uzoh, F. C. C. (2012). Seasonal variation in surface fuel moisture between unthinned and thinned mixed conifer forest, northern California, USA. *International Journal of Wildland Fire*, *21*(4), 428. https://doi.org/10.1071/WF11056

Faiella, S. M., & Bailey, J. D. (2007). Fluctuations in fuel moisture across restoration treatments in semi-arid ponderosa pine forests of northern Arizona, USA. *International Journal of Wildland Fire*, *16*(1), 119. https://doi.org/10.1071/WF06018

Family Forest Research Center. (2020). *Family Forest Owners*. https://www.familyforestresearchcenter.org/about-us/

Ficko, A., & Boncina, A. (2013). Probabilistic typology of management decision making in private forest properties. *Forest Policy and Economics*, *27*, 34–43. https://doi.org/10.1016/j.forpol.2012.11.001

Finley, A. O., & Kittredge, D. B. (2006). Thoreau, Muir, and Jane Doe: Different Types of Private Forest Owners Need Different Kinds of Forest Management. *Northern Journal of Applied Forestry*, *23*(1), 27–34. https://doi.org/10.1093/njaf/23.1.27

Forzieri, G., Dakos, V., McDowell, N. G., Ramdane, A., & Cescatti, A. (2022). Emerging signals of declining forest resilience under climate change. *Nature*, *608*(7923), 534–539. https://doi.org/10.1038/s41586-022-04959-9

Fraver, S., White, A. S., & Seymour, R. S. (2009). Natural disturbance in an old-growth landscape of northern Maine, USA. *Journal of Ecology*, *97*(2), 289–298. https://doi.org/10.1111/j.1365-2745.2008.01474.x

Frey, S. J. K., Hadley, A. S., Johnson, S. L., Schulze, M., Jones, J. A., & Betts, M. G. (2016). Spatial models reveal the microclimatic buffering capacity of old-growth forests. *Science Advances*, *2*(4), e1501392. https://doi.org/10.1126/sciadv.1501392

Fridley, J. D. (2009). Downscaling Climate over Complex Terrain: High Finescale (<1000 m) Spatial Variation of Near-Ground Temperatures in a Montane Forested Landscape (Great Smoky Mountains)*. *Journal of Applied Meteorology and Climatology*, *48*(5), 1033–1049. https://doi.org/10.1175/2008JAMC2084.1

Gallagher, M. R., Maxwell, A. E., Guillén, L. A., Everland, A., Loudermilk, E. L., & Skowronski, N. S. (2021). Estimation of Plot-Level Burn Severity Using Terrestrial Laser Scanning. *Remote Sensing*, *13*(20), 4168. https://doi.org/10.3390/rs13204168

Geiger, R., Aron, R. H., & Todhunter, P. (2012). *The Climate Near the Ground* (5th ed.). Vieweg+Teubner Verlag Wiesbaden.

Golladay, S. W., Martin, K. L., Vose, J. M., Wear, D. N., Covich, A. P., Hobbs, R. J., Klepzig, K. D., Likens, G. E., Naiman, R. J., & Shearer, A. W. (2016). Achievable future conditions as a framework for guiding forest conservation and management. *Forest Ecology and Management*, *360*, 80–96. https://doi.org/10.1016/j.foreco.2015.10.009

Greiser, C., Meineri, E., Luoto, M., Ehrlén, J., & Hylander, K. (2018). Monthly microclimate models in a managed boreal forest landscape. *Agricultural and Forest Meteorology*, *250–251*, 147–158. https://doi.org/10.1016/j.agrformet.2017.12.252

Grotta, A. T., Creighton, J. H., Schnepf, C., & Kantor, S. (2013). Family Forest Owners and Climate Change: Understanding, Attitudes, and Educational Needs. *Journal of Forestry*, *111*(2), 87–93. https://doi.org/10.5849/jof.12-052

Hansen, A. J., Neilson, R. P., Dale, V. H., Flather, C. H., Iverson, L. R., Currie, D. J., Shafer, S., Cook, R., & Bartlein, P. J. (2001). Global Change in Forests: Responses of Species, Communities, and Biomes. *BioScience*, *51*(9), 765. https://doi.org/10.1641/0006-3568(2001)051[0765:GCIFRO]2.0.CO;2

Hashida, Y., & Lewis, D. J. (2019). The Intersection between Climate Adaptation, Mitigation, and Natural Resources: An Empirical Analysis of Forest Management. *Journal of the Association of Environmental and Resource Economists*, *6*(5), 893–926. https://doi.org/10.1086/704517

Hengst-Ehrhart, Y. (2019). Knowing is not enough: Exploring the missing link between climate change knowledge and action of German forest owners and managers. *Annals of Forest Science*, *76*(4), 94. https://doi.org/10.1007/s13595-019-0878-z

Holden, Z. A., & Jolly, W. M. (2011). Modeling topographic influences on fuel moisture and fire danger in complex terrain to improve wildland fire management decision support. *Forest Ecology and Management*, *262*(12), 2133–2141. https://doi.org/10.1016/j.foreco.2011.08.002

Huff, E. S., Leahy, J. E., Kittredge, D. B., Noblet, C. L., & Weiskittel, A. R. (2017). Psychological distance of timber harvesting for private woodland owners. *Forest Policy and Economics*, *81*, 48–56. https://doi.org/10.1016/j.forpol.2017.04.007

IPCC. (2021). *Climate Change 2021: The Physical Science Basis*.

Janowiak, M., Mahaffey, A., & Riely, C. (2020). *Moving the needle: A review of needs to increase climate adaptation in the forests of New England*.

Jansujwicz, J. S., Calhoun, A. J. K., Leahy, J. E., & Lilieholm, R. J. (2013). Using Mixed Methods to Develop a Frame-Based Private Landowner Typology. *Society & Natural Resources*, *26*(8), 945–961. https://doi.org/10.1080/08941920.2012.729294

Jolly, W. M., Cochrane, M. A., Freeborn, P. H., Holden, Z. A., Brown, T. J., Williamson, G. J., & Bowman, D. M. J. S. (2015). Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, *6*(1), 7537. https://doi.org/10.1038/ncomms8537

Jucker, T., Hardwick, S. R., Both, S., Elias, D. M. O., Ewers, R. M., Milodowski, D. T., Swinfield, T., & Coomes, D. A. (2018). Canopy structure and topography jointly constrain the microclimate of human-modified tropical landscapes. *Global Change Biology*, *24*(11), 5243–5258. https://doi.org/10.1111/gcb.14415

Juerges, N., Leahy, J., & Newig, J. (2020). A typology of actors and their strategies in multi-scale governance of wind turbine conflict within forests. *Land Use Policy*, *96*, 104691. https://doi.org/10.1016/j.landusepol.2020.104691

Kane, J. M. (2021). Stand conditions alter seasonal microclimate and dead fuel moisture in a Northwestern California oak woodland. *Agricultural and Forest Meteorology*, *308–309*, 108602. https://doi.org/10.1016/j.agrformet.2021.108602

Karppinen, H., Hänninen, M., & Valsta, L. (2018). Forest owners' views on storing carbon in their forests. *Scandinavian Journal of Forest Research*, *33*(7), 708–715. https://doi.org/10.1080/02827581.2018.1480800

Kašpar, V., Hederová, L., Macek, M., Müllerová, J., Prošek, J., Surový, P., Wild, J., & Kopecký, M. (2021). Temperature buffering in temperate forests: Comparing microclimate models based on ground measurements with active and passive remote sensing. *Remote Sensing of Environment*, *263*, 112522. https://doi.org/10.1016/j.rse.2021.112522

Kenefic, L. S., Kabrick, J. M., Knapp, B. O., Raymond, P., Clark, K. L., D'Amato, A. W., Kern, C. C., Vickers, L. A., Dey, D. C., & Rogers, N. S. (2021). Mixedwood silviculture in North America: The science and art of managing for complex, multi-species temperate forests. *Canadian Journal of Forest Research*, *51*(7), 921–934. https://doi.org/10.1139/cjfr-2020-0410

Khanal, P. N., Grebner, D. L., Munn, I. A., Grado, S. C., Grala, R. K., & Henderson, J. E. (2017). Typology of Nonindustrial Private Forest Landowners and Forestry Behavior: Implications for Forest Carbon Sequestration in the Southern US. *Small-Scale Forestry*, *16*(3), 419–434. https://doi.org/10.1007/s11842-017-9363-4

Latif, Z. A., & Blackburn, G. A. (2008). *Forest microclimate modelling using gap and canopy properties derived from LiDAR and hyperspectral imagery*. 8.

Lenart. (2014). Perceptions on Climate Change Correlate with Willingness to Undertake Some Forestry Adaptation and Mitigation Practices. *Journal of Forestry*, *112*(6). https://doi.org/10.5849/jof.13-051

Li, Y., Mei, B., & Linhares-Juvenal, T. (2019). The economic contribution of the world's forest sector. *Forest Policy and Economics*, *100*, 236–253. https://doi.org/10.1016/j.forpol.2019.01.004

Llewellyn, G., Sullivan, G., & Minichiello, V. (2004). Sampling in qualitative research. In *Handbook of Research Methods for Nursing and Health Science* (2nd ed., pp. 210–239). Pearson Education Australia. https://hdl.handle.net/1959.11/4859

Loudermilk, E. L., O'Brien, J. J., Goodrick, S. L., Linn, R. R., Skowronski, N. S., & Hiers, J. K. (2022). Vegetation's influence on fire behavior goes beyond just being fuel. *Fire Ecology*, *18*(1), 9, s42408-022-00132–00139. https://doi.org/10.1186/s42408-022-00132-9

Loudermilk, E. L., O'Brien, J. J., Mitchell, R. J., Cropper, W. P., Hiers, J. K., Grunwald, S., Grego, J., & Fernandez-Diaz, J. C. (2012). Linking complex forest fuel structure and fire behaviour at fine scales. *International Journal of Wildland Fire*, *21*(7), 882. https://doi.org/10.1071/WF10116

Maxwell, A. E., Gallagher, M. R., Minicuci, N., Bester, M. S., Loudermilk, E. L., Pokswinski, S. M., & Skowronski, N. S. (2023). Impact of Reference Data Sampling Density for Estimating Plot-Level Average Shrub Heights Using Terrestrial Laser Scanning Data. *Fire*, *6*(3), 98. https://doi.org/10.3390/fire6030098

McDowell, N. G., & Allen, C. D. (2015). Darcy's law predicts widespread forest mortality under climate warming. *Nature Climate Change*, *5*(7), 669–672. https://doi.org/10.1038/nclimate2641

McGann, T. C., Schattman, R. E., D'Amato, A. W., & Ontl, T. A. (2022). Climate Adaptive Management in the Northeastern United States: Common Strategies and Motivations of Rural and Urban Foresters. *Journal of Forestry*, fvac039. https://doi.org/10.1093/jofore/fvac039

Menge, J. H., Magdon, P., Wöllauer, S., & Ehbrecht, M. (2022). *Impacts of forest management on stand and landscape-level microclimate heterogeneity of European beech forests* [Preprint]. In Review. https://doi.org/10.21203/rs.3.rs-1922384/v1

Millar, C. I., Stephenson, N. L., & Stephens, S. L. (2007). CLIMATE CHANGE AND FORESTS OF THE FUTURE: MANAGING IN THE FACE OF UNCERTAINTY. *Ecological Applications*, *17*(8), 2145–2151. https://doi.org/10.1890/06-1715.1

Mitchell, R. J., Hiers, J. K., O'Brien, J., & Starr, G. (2009). Ecological Forestry in the Southeast: Understanding the Ecology of Fuels. *Journal of Forestry*, 7.

Morelli, T. L., Daly, C., Dobrowski, S. Z., Dulen, D. M., Ebersole, J. L., Jackson, S. T., Lundquist, J. D., Millar, C. I., Maher, S. P., Monahan, W. B., Nydick, K. R., Redmond, K. T., Sawyer, S. C., Stock, S., & Beissinger, S. R. (2016). Managing Climate Change Refugia for Climate Adaptation. *PLOS ONE*, *11*(8), e0159909. https://doi.org/10.1371/journal.pone.0159909

Muscolo, A., Sidari, M., & Mercurio, R. (2007). Influence of gap size on organic matter decomposition, microbial biomass and nutrient cycle in Calabrian pine (Pinus laricio, Poiret) stands. *Forest Ecology and Management*, *242*(2–3), 412–418. https://doi.org/10.1016/j.foreco.2007.01.058

Nagel, L. M., Palik, B. J., Battaglia, M. A., D'Amato, A. W., Guldin, J. M., Swanston, C. W., Janowiak, M. K., Powers, M. P., Joyce, L. A., Millar, C. I., Peterson, D. L., Ganio, L. M., Kirschbaum, C., & Roske, M. R. (2017). Adaptive Silviculture for Climate Change: A National Experiment in Manager-Scientist Partnerships to Apply an Adaptation Framework. *Journal of Forestry*, *115*(3), 167–178. https://doi.org/10.5849/jof.16-039

Ontl, T. A., Janowiak, M. K., Swanston, C. W., Daley, J., Handler, S., Cornett, M., Hagenbuch, S., Handrick, C., Mccarthy, L., & Patch, N. (2020). Forest Management for Carbon Sequestration and Climate Adaptation. *Journal of Forestry*, *118*(1), 86–101. https://doi.org/10.1093/jofore/fvz062

Parsons, R. A., Mell, W. E., & McCauley, P. (2011). Linking 3D spatial models of fuels and fire: Effects of spatial heterogeneity on fire behavior. *Ecological Modelling*, *222*(3), 679–691. https://doi.org/10.1016/j.ecolmodel.2010.10.023

Peterson St-Laurent, G., Oakes, L. E., Cross, M., & Hagerman, S. (2021). R–R–T (resistance–resilience–transformation) typology reveals differential conservation approaches across ecosystems and time. *Communications Biology*, *4*(1), 39. https://doi.org/10.1038/s42003-020-01556-2

Pickering, B. J., Duff, T. J., Baillie, C., & Cawson, J. G. (2021). Darker, cooler, wetter: Forest understories influence surface fuel moisture. *Agricultural and Forest Meteorology*, *300*, 108311. https://doi.org/10.1016/j.agrformet.2020.108311

Pinto, A., & Fernandes, P. (2014). Microclimate and Modeled Fire Behavior Differ Between Adjacent Forest Types in Northern Portugal. *Forests*, *5*(10), 2490–2504. https://doi.org/10.3390/f5102490

Pozner, E., Bar-On, P., Livne-Luzon, S., Moran, U., Tsamir-Rimon, M., Dener, E., Schwartz, E., Rotenberg, E., Tatarinov, F., Preisler, Y., Zecharia, N., Osem, Y., Yakir, D., & Klein, T. (2022). A hidden mechanism of forest loss under climate change: The role of drought in eliminating forest regeneration at the edge of its distribution. *Forest Ecology and Management*, *506*, 119966. https://doi.org/10.1016/j.foreco.2021.119966

Ross-Davis, A., & Broussard, S. (2007). A Typology of Family Forest Owners in North Central Indiana. *Northern Journal of Applied Forestry*, *24*(4), 282–289. https://doi.org/10.1093/njaf/24.4.282

Rothermel, R. C. (1983). *How to predict the spread and intensity of forest and range fires* (INT-GTR-143; p. INT-GTR-143). U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. https://doi.org/10.2737/INT-GTR-143

Roussel, J.-R., Auty, D., Coops, N. C., Tompalski, P., Goodbody, T. R. H., Meador, A. S., Bourdon, J.-F., De Boissieu, F., & Achim, A. (2020). lidR: An R package for analysis of Airborne Laser Scanning (ALS) data. *Remote Sensing of Environment*, *251*, 112061. https://doi.org/10.1016/j.rse.2020.112061

Sanczuk, P., De Pauw, K., De Lombaerde, E., Luoto, M., Meeussen, C., Govaert, S., Vanneste, T., Depauw, L., Brunet, J., Cousins, S. A. O., Gasperini, C., Hedwall, P.-O., Iacopetti, G., Lenoir, J., Plue, J., Selvi, F., Spicher, F., Uria-Diez, J., Verheyen, K., … De Frenne, P. (2023). Microclimate and forest density drive plant population dynamics under climate change. *Nature Climate Change*, *13*(8), 840–847. https://doi.org/10.1038/s41558-023-01744-y

Schroeder, M. J., & Buck, C. C. (1983). *Fire weather: A guide for application of meteorological information to forest fire control operations.* U.S. Dept. of Agriculture, Forest Service.

Schuurman, G., Cat, H.-H., Cole, D., Lawrence, D., Morton, J., Magness, D., Cravens, A., Covington, S., O'Malley, R., & Fisichelli, N. (2020). *Resist-accept-direct (RAD)—A framework for the 21st-century natural resource manager*. National Park Service. https://doi.org/10.36967/nrr-2283597

Seymour, R. S., White, A. S., & deMaynadier, P. G. (2002). Natural disturbance regimes in northeastern North America—Evaluating silvicultural systems using natural scales and frequencies. *Forest Ecology and Management*, *155*(1–3), 357–367. https://doi.org/10.1016/S0378-1127(01)00572-2

Silver, E. J., Leahy, J. E., Weiskittel, A. R., Noblet, C. L., & Kittredge, D. B. (2015). An Evidence-Based Review of Timber Harvesting Behavior among Private Woodland Owners. *Journal of Forestry*, *113*(5), 490–499. https://doi.org/10.5849/jof.14-089

Soucy, A., De Urioste-Stone, S., Rahimzadeh-Bajgiran, P., Weiskittel, A., & McGreavy, B. (2020). Understanding characteristics of forest professionals and small woodlot owners for communicating climate change adaptation. *Trees, Forests and People*, *2*, 100036. https://doi.org/10.1016/j.tfp.2020.100036

Sousa-Silva, R., Ponette, Q., Verheyen, K., Van Herzele, A., & Muys, B. (2016). Adaptation of forest management to climate change as perceived by forest owners and managers in Belgium. *Forest Ecosystems*, *3*(1), 22. https://doi.org/10.1186/s40663-016-0082-7

St. John, L., & Ogle, D. (2009). Green strips or vegetative fuel breaks. *USDA - Natural Resources Conservation Service*.

Stapley, E., O'Keeffe, S., & Midgley, N. (2022). Developing Typologies in Qualitative Research: The Use of Ideal-type Analysis. *International Journal of Qualitative Methods*, *21*, 160940692211006. https://doi.org/10.1177/16094069221100633

Starr, S., McConnell, T., Bruskotter, J., & Williams, R. (2015). Typology of Ohio, USA, Tree Farmers Based Upon Forestry Outreach Needs. *Environmental Management*, *55*(2), 308–320. https://doi.org/10.1007/s00267-014-0382-z

Stevens-Rumann, C. S., Kemp, K. B., Higuera, P. E., Harvey, B. J., Rother, M. T., Donato, D. C., Morgan, P., & Veblen, T. T. (2018). Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters*, *21*(2), 243–252. https://doi.org/10.1111/ele.12889

Tanskanen, H., Granström, A., Venäläinen, A., & Puttonen, P. (2006). Moisture dynamics of moss-dominated surface fuel in relation to the structure of Picea abies and Pinus sylvestris stands. *Forest Ecology and Management*, *226*(1–3), 189–198. https://doi.org/10.1016/j.foreco.2006.01.048

Thompson, K., Grime, J. P., & Mason, G. (1977). Seed germination in response to diurnal fluctuations of temperature. *Nature*, *267*(5607), 147–149. https://doi.org/10.1038/267147a0

Van De Water, K., & North, M. (2011). Stand structure, fuel loads, and fire behavior in riparian and upland forests, Sierra Nevada Mountains, USA; a comparison of current and reconstructed conditions. *Forest Ecology and Management*, *262*(2), 215–228. https://doi.org/10.1016/j.foreco.2011.03.026

Vandewiele, M., Geres, L., Lotz, A., Mandl, L., Richter, T., Seibold, S., Seidl, R., & Senf, C. (2023). Mapping spatial microclimate patterns in mountain forests from LiDAR. *Agricultural and Forest Meteorology*, *341*, 109662. https://doi.org/10.1016/j.agrformet.2023.109662

von Arx, G., Graf Pannatier, E., Thimonier, A., & Rebetez, M. (2013). Microclimate in forests with varying leaf area index and soil moisture: Potential implications for seedling establishment in a changing climate. *Journal of Ecology*, *101*(5), 1201–1213. https://doi.org/10.1111/1365-2745.12121

vonHedemann, N., & Schultz, C. A. (2021). U.S. Family Forest Owners' Forest Management for Climate Adaptation: Perspectives From Extension and Outreach Specialists. *Frontiers in Climate*, *3*, 674718. https://doi.org/10.3389/fclim.2021.674718

Walker, X. J. (2020). Fuel availability not fire weather controls boreal wildfire severity and carbon emissions. *Nature Climate Change*, *10*.

Wason, J. W., Bevilacqua, E., & Dovciak, M. (2017). Climates on the move: Implications of climate warming for species distributions in mountains of the northeastern United States. *Agricultural and Forest Meteorology*, *246*, 272–280. https://doi.org/10.1016/j.agrformet.2017.05.019

White, J. C., Wulder, M. A., Varhola, A., Vastaranta, M., Coops, N. C., Cook, B. D., Pitt, D., & Woods, M. (2013). A best practices guide for generating forest inventory attributes from airborne laser scanning data using an area-based approach. *The Forestry Chronicle*, *89*(06), 722–723. https://doi.org/10.5558/tfc2013-132

Whitehead et al., R. J. (2006). *Effect of a Spaced Thinning in Mature Lodgepole Pine on Within-Stand Microclimate and Fine Fuel Moisture Content*. 14.

Will, R. E., Wilson, S. M., Zou, C. B., & Hennessey, T. C. (2013). Increased vapor pressure deficit due to higher temperature leads to greater transpiration and faster mortality during drought for tree seedlings common to the forest–grassland ecotone. *New Phytologist*, *200*(2), 366–374. https://doi.org/10.1111/nph.12321

Woods, M., Lim, K., & Treitz, P. (2008). Predicting forest stand variables from LiDAR data in the Great Lakes St. Lawrence forest of Ontario. *The Forestry Chronicle*, *84*(6), 827–839. https://doi.org/10.5558/tfc84827-6

Zellweger, F., Coomes, D., Lenoir, J., Depauw, L., Maes, S. L., Wulf, M., Kirby, K. J., Brunet, J., Kopecký, M., Máliš, F., Schmidt, W., Heinrichs, S., den Ouden, J., Jaroszewicz, B., Buyse, G., Spicher, F., Verheyen, K., & De Frenne, P. (2019). Seasonal drivers of understorey temperature buffering in temperate deciduous forests across Europe. *Global Ecology and Biogeography*, *28*(12), 1774–1786. https://doi.org/10.1111/geb.12991

Zellweger, F., De Frenne, P., Lenoir, J., Rocchini, D., & Coomes, D. (2019). Advances in Microclimate Ecology Arising from Remote Sensing. *Trends in Ecology & Evolution*, *34*(4), 327–341. https://doi.org/10.1016/j.tree.2018.12.012

Zellweger, F., De Frenne, P., Lenoir, J., Vangansbeke, P., Verheyen, K., Bernhardt-Römermann, M., Baeten, L., Hédl, R., Berki, I., Brunet, J., Van Calster, H., Chudomelová, M., Decocq, G., Dirnböck, T., Durak, T., Heinken, T., Jaroszewicz, B., Kopecký, M., Máliš, F., … Coomes, D. (2020). Forest microclimate dynamics drive plant responses to warming. *Science*, *368*(6492), 772–775. https://doi.org/10.1126/science.aba6880

APPENDICES

APPENDIX A: Chapter 1 Supplement

Private Woodland Owner Interview Guide

Land ownership/background

1. How did you come to own this land?
2. How long have you owned it?
3. What were your reasons for acquiring (purchase vs inherit)?
4. How many parcels do you own?
5. Total acreage?

Past management

1. What do you manage for? What do you value about your land?
2. Do you think a forest needs to be managed to stay healthy?
3. Where do you get your information about forest management and/or forest health?
4. Do you work with a forester?
    a. What is your management plan?
    b. How often do you meet with them?
    c. How would you characterize your level of trust in them?
5. What kind of management have you implemented in the past?
6. Has your woodlot undergone any major changes since you've owned it?
7. Has your management style/philosophy changed over the years?

Climate change perceptions

1. What are your thoughts about climate change (both generally and specifically related to your property)?
2. Is climate change something you are concerned about?
3. Was any of your past management motivated by climate change?
4. Are you concerned about the future effects of climate change on your woods?

Future plans

1. Do you anticipate greater challenges or greater successes in your future management? (optimistic or pessimistic about future management?)
2. If you see X changes in the future, how would you respond? (pick 3 or 4 scenarios)
3. Do you have plans for future land hand-off or purchase?
    1. Inheritance?

APPENDIX B: Chapter 2 Supplement

Table B.1. Remotely sensed predictor variables used in random forest models. Variables zqx are stratified in steps of 5% (i.e., zq5-zq95). Variables zpcumx are stratified into 9 layers, with layer 1 being the lowest (i.e., zpcum1-zpcum9; see Woods et al. 2008). Entropy is a normalized Shannon vertical complexity index.

Variable	Description	Source
zmax	Max height	Airborne lidar
zmean	Mean height	
zsd	Std. deviation of height distribution	
zskew	Skewness of height distribution	
zkurt	Kurtosis of height distribution	
zentropy	Entropy of height distribution	
zqx	x^{th} percentile (quantile) of height distribution	
zpcumx	Cumulative percentage of return in the x^{th} layer	
imax	Max intensity	
imean	Mean intensity	
isd	Std. deviation of intensity	
ikurt	Kurtosis of intensity distribution	
extsCV	Canopy cover	
Exts_aspect	Aspect	
Exts1	NDVI	Sentinel-2
Exts2	PC1	
Exts3	PC2	
Exts4	Red band	
Exts5	Green band	
Exts6	Blue band	
Exts7	Near-infrared band	

Table B.2. Comparison of linear mixed models (LMMs) predicting daily temperature range (DTR) for each season of the study period. The formula for all seasonal models is $DTR \sim CO + EGC$, where CO = canopy openness and EGC = evergreen cover. Interactions were included for CO * EGC when significant. For each variable in the table, the coefficient is listed above the *(standard error)* for that coefficient. Other model performance outputs can be found in the bottom rows, along with a key for statistical significance.

Variable	**Winter-2022**	**Spring-2022**	**Summer-2022**	**Autumn-2022**	**Winter-2023**	**Spring-2023**	**Summer-2023**
CO	0.034***	0.026**	0.064***	0.052***	0.033***	0.021*	0.056***
(SE)	*(0.007)*	*(0.008)*	*(0.007)*	*(0.007)*	*(0.006)*	*(0.010)*	*(0.007)*
EGC	−0.019*	0.035 ***	0.007	−0.006	−0.016*	−0.038**	0.003
(SE)	*(0.008)*	*(0.009)*	*(0.008)*	*(0.008)*	*(0.006)*	*(0.012)*	*(0.008)*
CO * EGC		0.001*				0.001**	
(SE)		*(0.000)*				*(0.000)*	
Num. Obs.	4124	4764	4808	4664	4193	4292	4324
R^2 Marg.	0.064	0.061	0.142	0.127	0.082	0.058	0.098
R^2 Cond.	0.097	0.074	0.184	0.159	0.085	0.075	0.116

+$p < 0.1$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Table B.3. Comparison of linear models (LMs) predicting mean daily temperature range (DTR_{mean}) for each season of the study period. The formula for all seasonal models is $DTR_{mean} \sim CO + EGC$, where CO = canopy openness and EGC = evergreen cover. Interactions were included for CO * EGC when significant. For each variable in the table, the coefficient is listed above the *(standard error)* for that coefficient. Other model performance outputs can be found in the bottom rows, along with a key for statistical significance.

Variable	**Winter-2022**	**Spring-2022**	**Summer-2022**	**Autumn-2022**	**Winter-2023**	**Spring-2023**	**Summer-2023**
CO	0.028**	0.023**	0.061***	0.055***	0.033***	0.021*	0.056***
(SE)	*(0.009)*	*(0.008)*	*(0.007)*	*(0.008)*	*(0.006)*	*(0.010)*	*(0.007)*
EGC	−0.018+	−0.038***	0.003	−0.005	−0.017*	−0.038**	0.003
(SE)	*(0.010)*	*(0.009)*	*(0.008)*	*(0.009)*	*(0.006)*	*(0.011)*	*(0.007)*
CO * EGC		−0.001*				−0.001**	
(SE)		*(0.000)*				*(0.000)*	
Num. Obs.	58	55	57	58	47	47	47
R^2	0.394	0.621	0.690	0.649	0.704	0.587	0.715

+$p < 0.1$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Table B.4. Comparison of linear mixed-effects models predicting daily maximum vapor pressure deficit (VPD_{max}) for each season of the study period. The formula for all seasonal models is $VPD_{max} \sim CC + EGC$, where CC = canopy openness and EGC = evergreen cover. Interactions were included for CC * EGC when significant. For each variable in the table, the coefficient is listed above the *(standard error)* for that coefficient. Other model performance outputs can be found in the bottom rows. +$p < 0.1$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Variable	**Spring-2022**	**Summer-2022**	**Autumn-2022**	**Spring-2023**	**Summer-2023**
CO	0.001	0.008***	0.005***	0.001	0.008***
(SE)	*(0.002)*	*(0.002)*	*(0.001)*	*(0.002)*	*(0.002)*
EGC	−0.003	−0.003	−0.002	−0.003	−0.001
(SE)	*(0.002)*	*(0.002)*	*(0.001)*	*(0.002)*	*(0.002)*
CO * EGC					
(SE)					
Num.Obs.	1840	1731	1712	1656	1656
R^2 Marg.	0.030	0.151	0.162	0.027	0.117
R^2 Cond.	0.030	0.177	0.162	0.027	0.125

Table B.5. Comparison of linear models predicting average daily maximum vapor pressure deficit ($VPD_{max\text{-}mean}$) for each season of the study period. The formula for all seasonal models is $VPD_{max\text{-}mean} \sim CC + EGC$, where CC = canopy openness and EGC = evergreen cover. Interactions were included for CC * EGC when significant. For each variable in the table, the coefficient is listed above the *(standard error)* for that coefficient. Other model performance outputs can be found in the bottom rows. +$p < 0.1$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Variable	**Spring-2022**	**Summer-2022**	**Autumn-2022**	**Spring-2023**	**Summer-2023**
CO	0.001	0.008***	0.005**	0.001	0.008***
(SE)	*(0.001)*	*(0.002)*	*(0.001)*	*(0.001)*	*(0.002)*
EGC	−0.003*	−0.003	−0.003+	−0.003*	−0.001
(SE)	*(0.001)*	*(0.002)*	*(0.001)*	*(0.001)*	*(0.002)*
CO * EGC					
(SE)					
Num.Obs.	20	20	20	18	18
R^2	0.646	0.787	0.779	0.652	0.797

Table B.6. Random forest model performance. R^2 is a pseudo r-square derived from a linear model of observed vs. predicted values of DTR. RMSE is root mean square error and CV is coefficient of variation.

Metric	**Winter-2022**	**Spring-2022**	**Summer-2022**	**Autumn-2022**	**Winter-2023**	**Spring-2023**	**Summer-2023**
R^2	0.15	0.32	0.59	0.46	0.36	0.31	0.53
Mean bias	0.09	0.07	0.10	0.10	0.09	0.09	0.07
RMSE	1.62	1.53	1.34	1.44	1.09	1.50	1.14
CV	17.47	12.91	11.22	15.09	13.42	12.36	12.72
Cor_cutoff	0.87	0.87	0.87	0.87	0.87	0.87	0.87

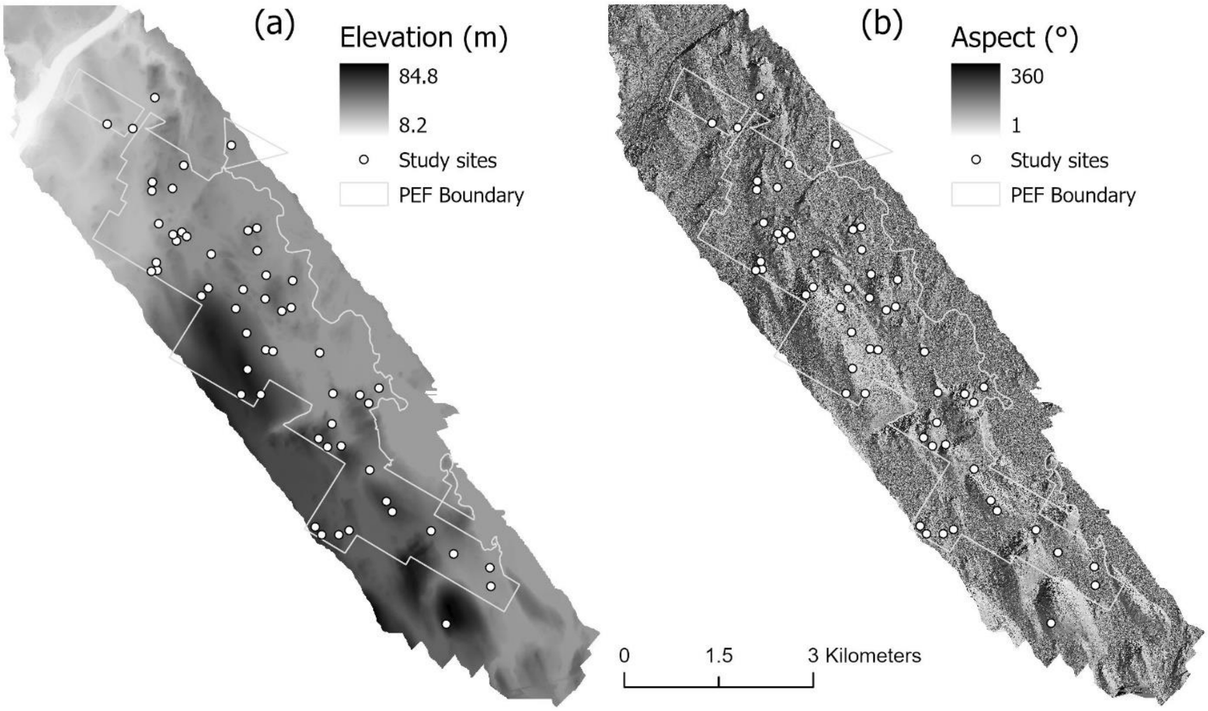


Figure B.1. Microclimate study sites in and around the Penobscot Experimental Forest (PEF) overlaid on topographical models. a) digital elevation model and **b)** aspect model derived from airborne laser scanning.

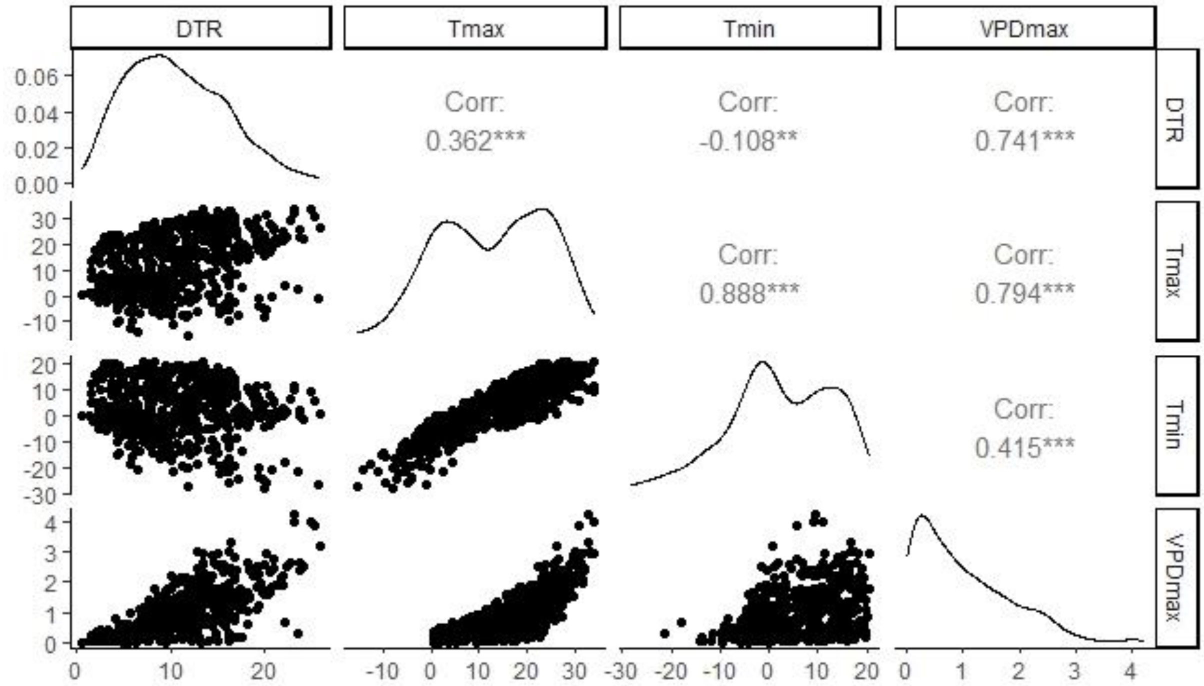


Figure B.2. Pair plots of microclimate response variables averaged across all study sites: daily temperature range (DTR), daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), and daily maximum vapor pressure deficit (VPD_{max}). Diagonal boxes display the density plot for each variable. Boxes in upper right display the Pearson's correlation coefficient for each pair. Stars show significant correlation, where **p < 0.01 and ***p < 0.001.

Figure B.3. Microclimate sensor shield design.

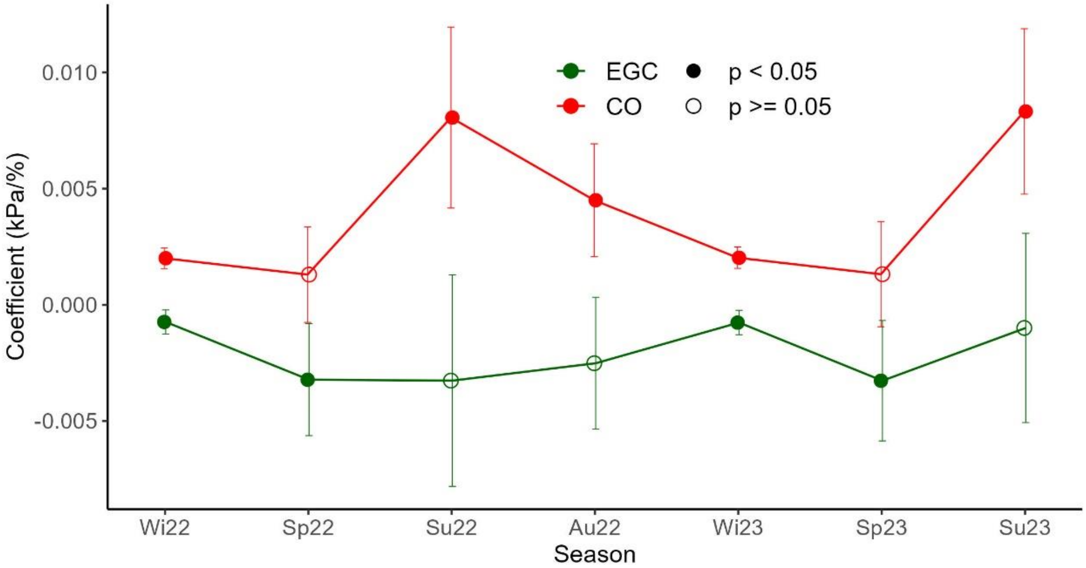


Figure B.4. Coefficients for canopy openness (CO) and evergreen cover (EGC) predictor variables in seasonal models of VPD_{max}. Model formula was VPD_{max} ~ CO + EGC. Filled point symbols denote significant non-zero coefficients (p-value < 0.05) and open point symbols denote insignificant coefficients.

APPENDIX C: Chapter 3 Supplement

Table C.1. Forest inventory summaries with one standard error for each study location, showing basal area (BAPA), trees per acre (TPA), canopy openness (CO) and evergreen cover (EGC).

Location	BAPA (ft^2/ac)	TPA	CO (%)	EGC (%)
Penobscot	103 ± 24.6	701 ± 111	46 ± 9.8	52 ± 7.9
Zealand	92 ± 24.1	1028 ± 228	44 ± 10.8	37 ± 6.4

Table C.2. Description of variables derived from terrestrial laser scanning (TLS), as defined by Gallagher et al., 2021 and Maxwell et al., 2023.

Variable	Description
zmax	Max height
zmean	Mean height
zsd	Std. deviation of height distribution
zskew	Skewness of height distribution
zkurt	Kurtosis of height distribution
zentropy	Entropy of height distribution:
zqx	x^{th} percentile (quantile) of height distribution
zpcumx	Cumulative percentage of return in the x^{th} layer
X_cnt	Number of X returns
X_per	Percent of total returns for X
hrX	Estimated fuel timelag class (e.g., 10-hour)
Stratification	**Definition**
ground	Points classified as ground
nground	Points classified as not ground
L1	Substrate (height > 0.001 m & height ≤ 0.3 m)
L2	Herbs and low shrubs (height > 0.3 m & height ≤ 1 m)
L3	Tall shrubs (height > 1 m & height ≤ 3 m)
L4	Pole-size trees and tall trees (height > 3 m)

Table C.3. Microclimate summaries for each study location, showing mean daily maximum temperature (T_{max}) and mean daily minimum relative humidity (RH_{min}) for all sites for the entire study period (7/7/23-9/6/23).

Location	**T_{max} (°C)**	**RH_{min} (%)**
Penobscot	28 ± 0.03	55 ± 0.13
Zealand	24 ± 0.03	67 ± 0.14

Table C.4. Model performance of the top AICc selected models predicting T_{max} from traditional forest inventory metrics. BAPA = basal area (sq.ft./ac); CO = canopy openness (%); R^2_m = marginal r-square; R^2_c = conditional r-square; RMSE = root mean square error; nRMSE = normalized root mean square error.

Predictors	**R^2_m**	**R^2_c**	**RMSE**	**nRMSE**
BAPA	0.387	0.891	1.90	0.071
CO	0.424	0.854	1.84	0.068
BAPA + CO	0.4334	0.909	1.74	0.065

Table C.5. Model performance of the top AICc selected models predicting RH_{min} from traditional forest inventory metrics. BAPA = basal area (sq.ft./ac); CO = canopy openness (%);(%); R^2_m = marginal r-square; R^2_c = conditional r-square; RMSE = root mean square error; nRMSE = normalized root mean square error.

Predictors	**R^2_m**	**R^2_c**	**RMSE**	**nRMSE**
BAPA	0.395	0.900	5.78	0.094
CO	0.425	0.855	5.65	0.092
BAPA + CO	0.425	0.855	5.30	0.086

Table C.6. Model performance of the top AICc selected models predicting FMC from traditional forest inventory metrics. BAPA = basal area (sq.ft./ac); CO = canopy openness (%); TPA = trees per acre; R^2_m = marginal r-square; R^2_c = conditional r-square; RMSE = root mean square error.

Predictors	**R^2_m**	**R^2_c**	**RMSE**
CO	0.512	0.600	2.21
BAPA + TPA	0.664	0.708	1.83
BAPA	0.449	0.607	2.31
BAPA + CO	0.520	0.638	2.14
CO + TPA	0.618	0.642	2.01

Table C.7. Model performance of the top AICc selected models predicting FMC from microclimate metrics. T_{max} = daily maximum temperature (°C); RH_{min} = daily minimum relative humidity (%); R^2_m = marginal r-square; R^2_c = conditional r-square; RMSE = root mean square error.

Predictors	**R^2_m**	**R^2_c**	**RMSE**
RH_{min}	0.705	0.898	1.59
RH_{min} + T_{max}	0.710	0.897	1.57
T_{max}	0.709	0.896	1.57

Table C.8. Model performance of the top AICc selected models predicting FMC from TLS metrics. Per_gap = percent of returns occurring in gaps; s_l5_prop_sd = standard deviation of returns occurring above 2-meter height; R^2_m = marginal r-square; R^2_c = conditional r-square; RMSE = root mean square error.

Predictors	R^2_m	R^2_c	RMSE
per_gap + s_l5_prop_sd	0.727	0.798	1.63
per_gap	0.493	0.686	2.26

Figure C.1. Microclimate and fuel moisture array established at each site.

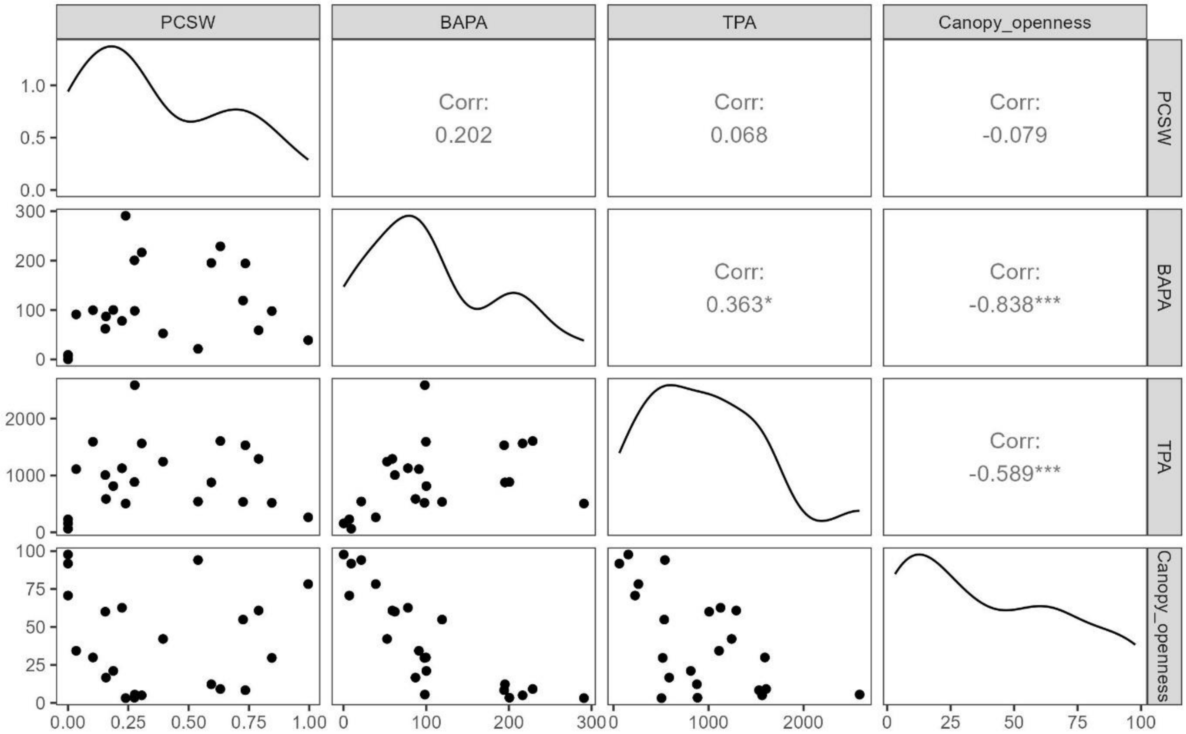


Figure C.2. Pair plots of forest structure metrics measured with traditional forest inventory. PCSW = evergreen cover; BAPA = basal area per acre; TPA = trees per acre. Correlation values refer to Pearson's r coefficient.

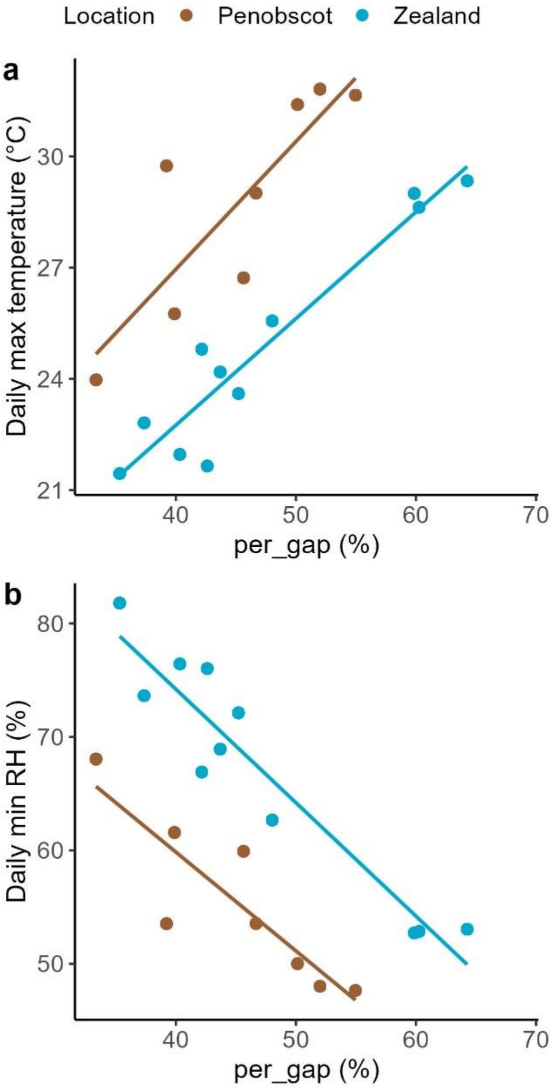


Figure C.3. Bivariate relationships between terrestrial laser scanning (TLS) and microclimate. Each panel shows the top individual TLS-derived predictor of **a)** Daily maximum temperature (T_{max}) and **b)** daily minimum relative humidity (RH_{min}).

BIOGRAPHY OF THE AUTHOR

Peter Breigenzer was born in Glasgow, Montana. He was raised on his family's multi-generational wheat farm where he learned the value of working the land through manual labor and heavy equipment operation at a young age. He received two bachelor's degrees from the University of Montana in Organismal Biology & Ecology and Environmental Studies in 2016. During and after college, he worked four seasons on various fuels, fire, and forestry crews in the northern Rocky Mountains, followed by two years as a data analyst in an environmental chemistry laboratory. After receiving his degree, he looks forward to pursuing a career supporting forest management through fire and fuels research. Peter is a candidate for the Master of Science degree in Forest Resources from the University of Maine in December 2023.