DISSERTATION

SPATIOTEMPORAL AGENT-BASED MODEL EXPLORATIONS OF WHITE-TAILED DEER MANAGEMENT IN NEW ENGLAND

Submitted by

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ABSTRACT

SPATIOTEMPORAL AGENT-BASED MODEL EXPLORATIONS OF WHITE-TAILED DEER MANAGEMENT IN NEW ENGLAND

This dissertation research addresses the intricate challenge of managing white-tailed deer (*Odocoileus virginianus*, henceforth "WTD") populations in the New England region while considering evolving ecological dynamics, changing interests of various stakeholders, and the role of management coordination among municipalities across scales. With a mixed-methods approach, I integrate qualitative and quantitative techniques such as agent-based modeling and case study analysis, helping to contribute multifaceted insights into the realm of WTD management in the region.

In Chapter 2, I focus on investigating the role of hunter recruitment and land access in shaping local WTD populations across 11 focal towns in New England. The purpose of this chapter is to explore how these factors influence WTD populations, specifically by identifying the thresholds at which they become significant drivers in controlling these populations. To achieve this, I employ a mixed-methods approach that combines ecological modeling and the analysis of empirical data. The study's results emphasize the specific thresholds of hunting land access required to trigger a decline in WTD populations for different hunter density scenarios. I estimate that in most towns, the existing combination of hunter density and land access is effective in managing local WTD populations. However, under conditions of declining hunter recruitment, towns may require higher amounts of hunting access to achieve similar levels of population control. These findings underscore the significance of addressing issues related to

declining hunter numbers and enhancing opportunities for hunting to sustain effective deer population management the region. This chapter's implications stress the importance of adaptive strategies and community engagement in the realm of WTD management in New England.

In Chapter 3, I assess the role of sharpshooting as a potential urban WTD management strategy across various contexts in New England. The chapter's primary purpose is to examine the feasibility of sharpshooting when factors like declining hunter numbers and limited hunting land access impact the efficacy of current deer management approaches. I conduct this investigation using a mixed-methods approach, combining ecological modeling with social science surveys and assessments. The results from this chapter offer insights into the role of sharpshooting as a strategy if the effectiveness of hunting diminishes. The findings suggest that most of the towns studied can effectively manage WTD populations without the need for sharpshooting. However, as hunter recruitment declines and hunting access becomes more limited, sharpshooting may become a reasonable solution when it aligns with community preferences. This chapter concludes that sharpshooting can serve as a management tool in certain scenarios, emphasizing the significance of prioritizing stakeholder education, engagement, and acceptance. The implications drawn from this research underscore the need for community involvement in shaping management decisions, particularly in relation to adopting sharpshooting for local WTD population control.

In Chapter 4, I focus on the broader theme of WTD management coordination in New England, examining its implications in controlling WTD populations across spatial scales. The main purpose of this chapter is to assess the impacts of stakeholder cooperation and coordination among municipalities on the effectiveness of WTD population management. My methodology involves the development and application of theoretical agent-based models to simulate different coordination scenarios. The chapter's results consistently demonstrate the significant role of coordination in shaping management outcomes, both within individual towns and across multiple municipalities. Based on model outcomes, effective cooperation between neighboring towns consistently leads to lower WTD densities both in towns with and without active management, exemplifying the role of collaborative efforts at larger scales. Additionally, the findings highlight the need for flexible strategies that consider the unique circumstances of each municipality. When aligned with community interests, the results demonstrate the potential for significant reductions in WTD densities with coordinated lethal management efforts, offering a path for more successful WTD population management in New England and similar regions. The implications of this chapter emphasize the role of regional cooperation and the importance of tailoring management strategies to specific contexts and community dynamics.

This research not only contributes insights into the complexity of WTD management in New England, but it also serves as a broader blueprint for wildlife management worldwide. I encourage other researchers to build agent-based models to inform management of other situations and species across geographical locations and contexts. In this research, I reveal that the challenge of managing WTD populations largely arises from the spatially heterogeneous distribution of WTD and resulting conflicts, in addition to the complexity of achieving stakeholder consensus across spatial scales. This demonstrates the tradeoff between accommodating diverse stakeholders and achieving regional WTD population control. With adaptive, science-based, and community-based approaches, I explore the roles of adaptability, collaboration, and innovation in contributing to sustainable WTD management efforts. In the end, I hope this research contributes to informing management practices, promoting a balanced and harmonious coexistence between humans and resident wildlife in a changing world.

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1. INTRODUCTION

In the Northeastern US, the timeless dance between humans and white-tailed deer (*Odocoileus virginianus*, henceforth referred to as "WTD" or "deer") takes center stage. As deer numbers climb, hunter engagement wanes, and access to hunting grounds dwindles, a new chapter of modern management unfolds. This is a story that brings together the dimensions of wildlife, humanity, and the captivating interplay between them. WTD represent a species both cherished and challenged by their interactions with our evolving anthropocentric landscape (Kelly 2018). As deer populations continue to rise and hunters and land access decrease in the region (Knoche and Lupi 2012, Tack et al. 2018), novel conflicts have emerged such as how to effectively manage WTD populations while accommodating diverse stakeholder interests and ecological concerns (Leong et al. 2009). This study endeavors to tackle this multifaceted challenge by exploring impacts of decreased hunter density and hunting land access through a case study analysis in addition to assessing implications of sharpshooting and management coordination. The overarching goal is to gain insights into the ecological, social, and theoretical dynamics of WTD management and to promote informed, science-based, sustainable wildlife management approaches.

I expand the definition of New England to encompass Maine, Vermont, New Hampshire, Massachusetts, Connecticut, Rhode Island, and notably, New York (henceforth collectively referred to as "New England"). While New York is not conventionally considered part of this region, its inclusion is paramount for this research due to its pivotal role and significance in the context of project implications. In this study, I concentrate on data collected from both New York (hereafter "NY") and Massachusetts (hereafter "MA"), with broader implications applying to the greater New England region. The study team—consisting of members from Boston University, Colorado State University, Texas A&M University, and the University of Wisconsin-Madison—collected a variety of data from 11 focal towns (NY: Clay, DeWitt, Fenner, Geddes, Manlius; MA: Carlisle, Easton, Lincoln, Pepperell, Sharon, Weston) across 4 years (2019 – 2023) to assess socioecological dynamics surrounding WTD management. In NY and MA, WTD are managed by their state wildlife agencies: MassWildlife and the New York State Department of Environmental Conservation, respectively. In this dissertation, I refer to a concept called the "New England WTD management system" or "management landscape". These phrases may imply some level of synchrony, though this research will investigate to what level coordination actually exists.

New England's landscapes encompass bustling urban centers, sprawling suburbs, and rural expanses. From the rolling farmlands of New York to the coastal woodlands of Massachusetts, the region offers a range of diverse habitats for WTD (NLCD, MRLC, USGS, https://www.mrcl.gov/, accessed 2019). These landscapes play an important role in shaping deer distribution and behavior, impacting individual patterns such as dispersal distances (Gilbertson et al. 2022) and emergent population phenomena such as carrying capacity (Mcshea 2012). Deer frequently and easily adapt to human dominated areas such as urban and suburban environments, further influencing their dynamics and introducing new avenues of human-wildlife conflict (Storm et al. 2007, Droe 2021). Within this mosaic of environments lies the challenge of managing WTD populations in alignment with intricate social and ecological goals (Chase et al. 2000).

New England, like many regions across North America, has experienced a significant increase in WTD population sizes in recent decades (Decker and Connelly 1990, McDonald et al.

2007, NYSDEC 2007, n.d.). Factors contributing to this increase include changes in land use patterns, reduced predation, and a plentiful food supply (DeNicola et al. 2000, Fischer et al. 2015, Kelly 2018). The term "overabundance" is inherently subjective, but typically refers to WTD density perceived to exceed biological or cultural carrying capacities (Adams and LaFleur 2020). Overabundant WTD populations can lead to detrimental effects on both natural ecosystems and human communities (Boulanger et al. 2014). These impacts encompass issues such as damage to vegetation (Tremblay and Côté 2004, NDTC 2008), increased vehicle collisions (Conover et al. 1995), the spread of diseases such as Lyme disease (Clark and Bidaisee 2021), crop depletion (Tremblay and Côté 2004, Nugent et al. 2011), and disruptions in ecosystem nutrient cycling (Nuttle et al. 2011, NYSDEC 2018). Conversely, many studies acknowledge the important socioeconomic and ecological services provided by WTD when their numbers are in alignment with community preferences (Hanberry 2021).

In this management system, stakeholders play a pivotal role, each with their unique interests and concerns (Messmer et al. 1997, Leong et al. 2009). Key players include hunters, private landowners, animal rights activists, and state wildlife agencies. Though each stakeholder category is complex and consists of a range of views depending on individual experiences, there are trends in WTD population size preference (West and Parkhurst 1973, Stollkleemann and Welp 2006, Davies and White 2012). Hunters, who have long been at the forefront of deer population control, often seek to maintain steady or high deer populations for successful and enjoyable hunting experiences (Harper et al. 2012). Conservationists and ecologists generally advocate for balanced ecosystems, stressing the need to curb deer overpopulation to protect native vegetation and maintain biodiversity (Garrot 1993, Smith 2009, Simard et al. 2013). Similarly, farmers and landowners frequently grapple with garden and crop damage caused by deer and are keen on reducing their numbers to protect their land and livelihoods (Knoche and Lupi 2007). Amidst these diverse interests, settling on a community supported WTD management strategy presents a complex challenge. Navigating these competing interests and finding common ground is a central factor in successful deer management, requiring careful consideration of stakeholder perspectives and informed decision-making.

As deer populations rise, the number of hunters has been generally declining or holding steady in New England (Ryel 1968, Riley et al. 2003, Tack et al. 2018). Several factors contribute to this trend, including demographic shifts, changing interests among the younger generation, and increased urbanization (Winkler and Warnke 2013, Hewitt 2015, Kelly 2018). This decline in hunter recruitment poses a significant challenge for modern WTD management, especially in urban areas where hunting access is largely restricted (Siemer et al. 2004, Lerman et al. 2021). Hunters play a vital role in regulating deer populations, both historically and pivotally in current times (Kelly 2018). They help control deer numbers, maintain ecological balance, and contribute to funding conservation efforts through hunting license fees and taxes on hunting equipment (Brinkman et al. 2007, Harper et al. 2012, Hewitt 2015). A diminishing pool of hunters means fewer resource tools for wildlife management and an increased reliance on alternative strategies, such as sharpshooting, which has its own complexities and challenges (Frank et al. 1993, Messmer et al. 1997, Warren 2000, DeNicola and Williams 2008, Figura 2017*a*). To assess the feasibility of various management solutions, it is important to understand the role of management coordination across spatial scales.

The global demand for research on wildlife management coordination is evident in the literature (Casebeer 1978, Valdez et al. 2006, Feng et al. 2021). Many regions worldwide lack formal deer management systems (Pérez-Espona et al. 2009), potentially leading to challenges in effective management due to insufficient coordination (Hall and Gill 2010, Fattorini et al. 2020). Studies have documented that deer populations can proliferate without coordinated management, oftentimes conflicting with community goals depending on stakeholder perspectives (Finch and Baxter 2007). Some countries have established international partnerships like the Canada–Mexico–United States Trilateral Committee for Wildlife and Ecosystem Conservation and Management to foster collaboration in wildlife management across borders (Valdez et al. 2006). National deer management institutions, such as The Deer Commission for Scotland, oversee deer management at the country level, addressing conflicts as needed (Deer Commission for Scotland 2001, Pérez-Espona et al. 2009). On a local scale, programs like The Deer Initiative in England and Wales promote coordinated, sustainable deer management within specific regions (The Deer Initiative Limited n.d., Pérez-Espona et al. 2009). These collaborative efforts demonstrate the increasing recognition of the importance of coordination in tackling deer management challenges across spatial scales.

Declining hunter recruitment and hunting access combined with increasing WTD populations underscores the need for a better understanding of WTD management systems and the development of effective solutions (Hewitt 2015, Tack et al. 2018). This challenge is at the heart of the research presented in the following chapters. Understanding WTD management systems requires a holistic approach that integrates ecological, social, and theoretical dimensions (Austin 2007, Baggio 2011, Levin et al. 2012, Strijker et al. 2020, Droe 2021). Research into this realm should involve examining functional relationships between key players e.g., deer, hunters, sharpshooters; Lindenmayer et al. 2012), studying how coordination among municipalities can influence management outcomes (Feit 1998, Feng et al. 2021), and engaging with diverse stakeholder groups who hold varying perspectives on WTD management (West and Parkhurst 1973, Stollkleemann and Welp 2006, Davies and White 2012).

The overarching problem that the following chapters collectively address is the complex challenge of managing New England WTD populations in the face of rapidly evolving social and ecological contexts. This multifaceted issue is characterized by several interconnected factors that have broader implications for wildlife management and conservation. The larger problem is not limited to New England; it reflects a global issue in wildlife management. Human-wildlife conflicts, ecosystem imbalances, and the changing dynamics of hunter participation are challenges faced by regions worldwide (Feit 1998, Davies and White 2012, Meek 2013, Feng et al. 2021). Solutions to these challenges can have far-reaching implications for the sustainability and health of coupled natural-human systems around the world.

1.1. Research Questions, Aims, and Objectives

In this study, I aim to navigate the complexities of managing WTD populations in New England through a case study analysis that merges ecological, social, and theoretical paradigms (Figure 1). Specifically, I ask:

> *How can New England WTD populations be effectively managed in the face of evolving ecological dynamics, shifting stakeholder interests, and the complexities of coordination among municipalities?*

Drawing insights from 3 interlinked chapters, this dissertation illuminates the ecological foundations, social intricacies, and theoretical underpinnings that collectively define WTD management in this region. Through this research, I investigate 3 core WTD management

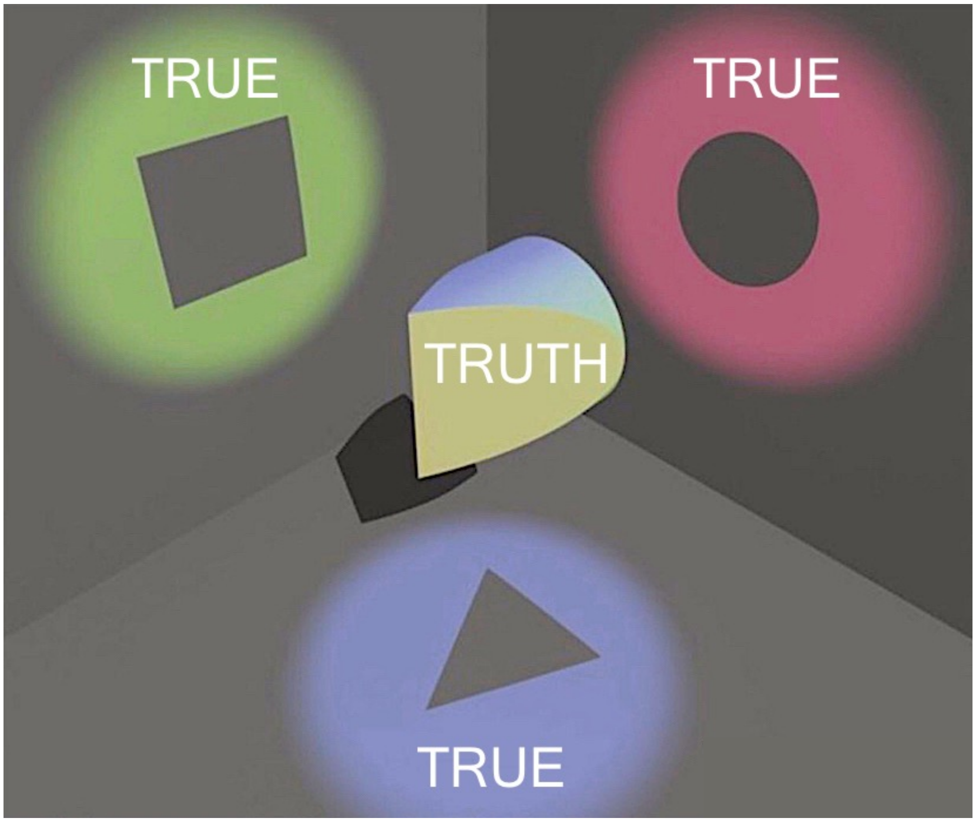


Figure 1. A graphical depiction of the methodological triangulation approach where multiple perspectives are combined to promote the generation of comprehensive results (Evoloshen 2023).

challenges, each examined within a separate chapter, yet all contributing to a well-rounded view of WTD management in New England.

Though these collective chapters, my aim is to explore the challenges and opportunities of WTD management systems in New England and their broader implications. This overarching goal revolves around understanding the impacts of reduced hunter recruitment and land access, examining the feasibility of sharpshooting as an alternate or supplementary management strategy, and assessing the influence of management coordination among municipalities on relevant dynamics. To achieve this overarching aim, specific objectives are as follows:

- Objective 1: Ecological Insights
    - Gain insights from employing an ecological agent-based model in a coupled natural-human system.
    - Investigate how different WTD management approaches influence WTD density.
    - Identify thresholds of management efficacy that reduce local WTD populations.
- Objective 2: Social Insights
    - Explore the diverse interests and perspectives of stakeholders involved in WTD management.
    - Assess the social acceptability of various WTD management strategies.
    - Investigate the role of stakeholder engagement in shaping WTD management decisions.
- Objective 3: Theoretical Insights
    - Examine the influence of coordination among municipalities on WTD management dynamics.
    - Assess the effectiveness of different management strategies and their spatial implications.
    - Investigate the spatial scale at which coordination becomes crucial for successful WTD management efforts.

These overarching aims and objectives link to a set of research questions (depicted below) that guide the collective inquiry:

- Ecological Questions
    - How do overabundant WTD populations impact local ecosystems, and what ecological challenges do they pose?

    - What is the influence of various WTD management approaches on the density of WTD populations within a given area?
    - Can specific thresholds of management efficacy be identified that effectively reduce local WTD populations?
- Social Questions
    - What are the diverse interests and perspectives of stakeholders involved in WTD management?
    - To what extent are various WTD management strategies socially acceptable among different stakeholder groups?
    - How does stakeholder engagement influence decision-making processes and outcomes in WTD management?
- Theoretical Questions
    - What is the impact of coordination among municipalities on the dynamics of WTD management efforts?
    - How effective are different WTD management strategies, and what are their spatial implications for population management?
    - At what spatial scale does coordination become crucial for the successful implementation of WTD management efforts across diverse landscapes and regions?

By addressing these questions, the chapters contribute to the development of sustainable and effective WTD management strategies by balancing the needs of ecosystems and human communities in the face of evolving and complex natural-human systems.

1.2. Significance and Justification

The significance and justification for this investigation stem from its timely, practical, and theoretical implications for advancing scientific discourse and promoting sustainable, informed, evidence-driven wildlife management approaches. Through this research, I unravel the ecological, social, and theoretical complexities involved in managing WTD populations in a changing world. By analyzing a range of management approaches, this study enhances our comprehension of how these strategies impact WTD density by pinpointing thresholds of management effectiveness. The findings contribute to the broader field of conservation ecology by highlighting the need for proactive management measures to promote sustainable interactions of ecosystems and communities. Through addressing these ecological inquiries, this research equips the academic field, wildlife managers, and stakeholders with new perspectives to maintain the ecological balance and integrity of our shared landscapes.

Beyond its ecological implications, this study has equally relevant social importance regarding New England WTD management systems. It navigates the complex web of stakeholder interests and perspectives involved, including a variety of key players with variable interest and power dynamics. By exploring the acceptability of different management strategies among diverse stakeholder groups, this research offers insights into the social dimensions that shape wildlife management solutions. Additionally, this study investigates the role of stakeholder engagement, demonstrating how the involvement of various groups informs the decision-making processes surrounding WTD management. By understanding stakeholder values and preferences, this project also contributes to the broader discourse of human-wildlife coexistence and the challenges of managing wildlife in human-dominated landscapes. In a world where community preferences and values are important considerations in conservation efforts, this research serves as a guide for fostering collaborative and informed decision-making, balancing the interests of stakeholders, and promoting sustainable approaches in New England WTD management systems.

This research also carries philosophical significance in examining the theoretical underpinnings of New England's WTD management systems. This includes the influence of coordination among municipalities on the dynamics of WTD management efforts, a topic of global relevance in wildlife management. Furthermore, this study evaluates the effectiveness of diverse management strategies and their spatial implications, offering theoretical insights that can inform future research and policy decisions alike. It also investigates the spatial scale at which coordination becomes an important consideration in the successful implementation of WTD management efforts. Within New England's complex natural-human systems and evolving ecological challenges, this research contributes to the broader theoretical framework of wildlife management, setting a precedent for addressing similar conflicts worldwide.

Collectively, the significance of the overall study lies in the interconnectedness of all chapters. The ecological, social, and theoretical dimensions that I address in the body chapters are not isolated; they are interdependent facets of a complex problem. The rising deer populations in New England intersect with social intricacies, in turn influencing the dynamics of these complex systems and shifting management effectiveness through space and time. Understanding these interconnections is important in developing informed and effective approaches to WTD management in New England. The broader significance of this dissertation transcends the boundaries of New England by offering a platform for others to draw insights from when developing of agent-based models for wildlife research. The framework of providing practical insights to focal communities can also guide wildlife management in human-dominated landscapes worldwide. Furthermore, the findings contribute to the theoretical foundations of wildlife management, exploring the potential role of coordination in achieving ecological and social goals. Collectively, this research underscores the necessity for adaptable, sustainable, science-driven management approaches to address the evolving challenges posed by wildlife populations in an ever-changing coupled natural-human environment.

1.3. Chapter Structure and Progression

This section functions as a roadmap, offering context for the forthcoming chapters while emphasizing the interconnectedness of the topics explored. I crafted these chapters with the intent to publish the middle 3 as standalone entities, each contributing to the overarching theme of WTD management dynamics in New England.

The purpose of Chapter 2 is to provide a detailed overview of the complexities associated with a shrinking WTD hunter population in conjunction with declining hunting land access in New England. I aim to identify thresholds of hunter density and hunting access required to start reducing local WTD populations for 11 focal towns, assess the overall efficacy of hunting in the region, and provide management recommendations for the focal towns. I also discuss the potential future challenges posed by declining hunter recruitment and limited hunting access and suggest strategies to mitigate negative ramifications. Additionally, I propose management recommendations for focal towns to encourage science-based, proactive, adaptive management in addressing local WTD conflicts. This chapter also provides insights into future research directions related to agent-based modeling, ecological science, and social science to advance our understanding of complex wildlife management systems.

Chapter 3 aims to assess the effectiveness and feasibility of sharpshooting as a management strategy for urban WTD populations in New England. Using a multifaceted approach that integrates agent-based models, empirical data, and stakeholder analyses, I address the multifaceted ecological and social dimensions of WTD sharpshooting across 11 New England focal towns. I explore whether municipalities can maintain their WTD populations without resorting to sharpshooting, or whether this approach may be valuable in certain contexts given the anticipated decline in hunter recruitment and land access. This research contributes to advancing the understanding of WTD sharpshooting feasibility in the context of New England, thereby promoting science-based, informed urban wildlife management approaches and fostering sustainable coexistence for both communities and resident WTD populations.

In Chapter 4, I explore the intricate dynamics of managing WTD populations in a rapidly evolving natural-human landscape. By examining the role of management coordination across scales and contexts, this chapter sets the stage for an informed understanding of the multifaceted challenges and opportunities in New England WTD management. Through a combination of theoretical insights, empirical data, and agent-based modeling, I aim to shed light on the complex interplay between ecological processes, social dynamics, and management strategies that shaped the past and inform the future of WTD populations and their coexistence with human communities in New England.

Chapter 5 serves as the culminating synthesis, bringing together the threads from the previous chapters to provide an inclusive understanding of WTD management dynamics in New England and their broader implications. In the conclusion chapter, I synthesize the findings from Chapters 2, 3, and 4, connecting themes and focusing on overarching takeaways. I discuss the significance, justification, and limitations of the overall study in detail. Collectively, the 3 chapters serve as a lens through which we can explore the complex nature of WTD management in New England. They provide a multifaceted examination of the challenges and opportunities of this system, contributing to the development of sustainable solutions that balance the needs of ecosystems and human communities in New England and beyond.

2. HOW LAND ACCESS AND HUNTER RECRUITMENT IMPACT WHITE-TAILED DEER MANAGEMENT EFFICACY IN NEW ENGLAND

2.1. Summary

With hunting recruitment and land access declining across New England, I call into question the sustainability of this historic management method in effectively managing local white-tailed deer populations (*Odocoileus virginianus*, henceforth "WTD"). My primary goal is to better understand the intricate dynamics governing these complex management systems, and in the process, reveal insights to inform contemporary management decisions. Through an agent-based model analysis of 11 New England focal towns, I explore specific scenarios across diverse social and ecological contexts relevant to stakeholder groups. The results suggest that most focal towns can successfully manage their local WTD populations through hunting practices based on current estimates. However, with an anticipated decline in the hunter population, the results imply that towns may need more open access than is currently available, introducing potential challenges. Additionally, with hunting access levels also in decline, the efficacy of hunting as a management strategy may increasingly diminish. The consideration of these impending hurdles should encourage proactive measures to not only maintain the efficacy of hunting, but also to adapt to the evolving landscape of modern wildlife management. I present social and ecological management recommendations for the focal towns, aiming to provide a foundation for informed decision-making in harmonizing ecological equilibriums with the interests of human communities.

2.2. Introduction

In the Northeastern US, where wild forests merge with urban communities, a novel challenge arises—one that extends its reach far beyond the landscapes of this region. It is a challenge that involves white-tailed deer (*Odocoileus virginianus*, henceforth "WTD" or "deer"), hunters, landowners, and policymakers alike as they navigate a balance between preserving tradition and managing the future. As I explore the complex roles of hunter density and hunting land access in New England WTD management, I uncover a story that encourages contemplation regarding the future of hunting and our responsibility in ecological stewardship. This is a tale that weaves together the threads of WTD biology and ecology, hunter density, and land access into an intricate narrative—a story of ecological harmony, social intricacies, and the quest to promote a sustainable future for communities and resident wildlife.

The historical trajectory of WTD in the US serves as a foundational backdrop for the current hunting practices that shape communities today. Native to North America, WTD populations were historically abundant across their range from Canada to Peru (Hewitt 2015). Exemplified by this broad range, WTD thrive in diverse ecosystems due to their adaptability, high reproductive rates, and density-dependent growth rates (Conover 1995, Post and Stenseth 1998, DeNicola et al. 2000, NDTC 2008, Fischer et al. 2015). They played a pivotal cultural role for early hunting communities (e.g., Native American tribes, European settlers) who relied on them for sustenance and trade over millennia (Cronon 1983, Kelly 2018). However, unregulated market hunting and habitat loss led to a significant decline in WTD populations with a low peak in the early 1900s, leaving sparse pockets of the species across the country (Heffelfinger et al. 2013, Hewitt 2015, Kelly 2018).

This decline had the most significant impact on hunters, making them the primary driving force behind efforts to restore the deer populations (Hewitt 2015). Their commitment, political ties, professional influence, and personal resources played a pivotal role in spearheading these recovery initiatives (Kelly 2018). They formed sportsman clubs to promote the implementation of management measures, including regulated hunting seasons, bag limits, and the creation of wildlife refuges, aimed at striking a balance between hunting opportunities and the preservation of viable deer populations for the future (Dart et al. n.d., Leopold 1933, Garrott et al. 1993, McCarthy and Possingham 2007, Kelly 2018). While enforcement was not stringent, the initial legislative effort to address low deer populations dates back to 1646 when Rhode Island prohibited deer hunting from spring through fall (Hewitt 2015). These early laws, along with numerous other that followed, were not motivated by conservation ethic but were driven by the economic necessity of having deer populations for the prosperity of the colonies (Kelly 2018). However, they inadvertently laid the foundation for deer conservation and contributed to the growing deer populations we see today.

With the rapid resurgence of WTD populations in the late 1900s, hunters continued to support the management of deer and consequently, the economic prosperity of the country. For example, hunting funds state agencies through taxation of guns and ammunition (Mahoney 2009, Knoche and Lupi 2012, Tack et al. 2018) and enables research that furthers the understanding of WTD ecology (Hewitt 2015). Hunting also transfers income from urban to rural communities as 42% of hunters come from cities to the countryside to purchase supplies and harvest deer (Hewitt 2015). The net economic value of WTD in America, after taking the difference from positive (e.g., hunting revenue, viewing) and negative (e.g., deer-vehicle collisions, agricultural damage) effects, is estimated to be $12.2 billion annually (Conover 2008). To sustain the viability of hunting in managing deer and its economic advantages, it is important to understand the unique motivations that drive each hunter's participation.

Deer are one of the most prized big game animals in North America, cherished by hunters for their abundance and challenging nature (Kelly 2018). Hunter motivations can vary by individual, which demonstrates the complex dynamics that shape this management system (Levin et al. 2012, Duda et al. 2021). Hunting can encompass various categories such as trophy, recreational, and/or subsistence hunting, contingent upon the unique motivations of each hunter (Cronon 1983, Riley et al. 2003, Brinkman et al. 2007, Hewitt 2015), Achievement-oriented hunters seek personal success in harvesting deer, affiliative-oriented hunters value companionship during the hunt, and appreciative-oriented hunters enjoy the outdoor experience, all of which have implications for deer management (Decker and Connelly 1973, Kelly 2018). A survey by Harper and Shaw (2012) revealed that most hunters participate to experience nature, are concerned about herd health, and desire quality deer management practices. Hunter motivations and beliefs can significantly influence the efficacy of hunting, and similarly, the diversity of other stakeholders can also impact the sustainability of this management method.

In the Northeastern US, key stakeholder groups in WTD management include hunters, private land owners, state wildlife agencies, government bodies, and the general public (Riley et al. 2003, Mahoney 2009, Winkler and Warnke 2013). Hunters have historically been the key stakeholder group in successful WTD management efforts, as their participation is central to actively managing rural deer populations (Ryel 1968, Riley et al. 2003, Conlin et al. 2009, Harper et al. 2012, Hewitt 2015, Tack et al. 2018). Private landowners hold substantial influence over the level of community access to hunting grounds (Thomas and Adams 1985, Ribot and Peluso 2003, Storm et al. 2007, Recce 2008, O'Shea 2009*a*), where wildlife agencies and government bodies create and enforce hunting-related policies (Nugent et al. 2011, Knoche and Lupi 2012, Levin et al. 2012). The values, beliefs, perceptions, and experiences of the general public shape local attitudes and in turn, can influence all other stakeholders and the ultimate efficacy of hunting in a community (West and Parkhurst 1973, Stollkleemann and Welp 2006, Smith 2009, Davies and White 2012, Bruckermann et al. 2021).

Based on community references, a variety of deer management methods can be employed, though hunting remains the most common strategy for controlling and maintaining WTD populations in the Northeastern US (NDTC 2008, Dickson et al. 2009, McShea 2012, Tack et al. 2018). Some municipalities have implemented sharpshooting, where trained professionals cull specific groups of deer in urban areas when hunting is restricted for safety reasons. While other communities may lean towards non-lethal management methods like fertility control or relocation, their impracticality often arises due to the high cost, time, and labor requirements associated with these methods. On rare occasions, there have been efforts to manage deer by restoring ecological balances such as through predator reintroductions, exemplified by the well-known cases of wolves in Yellowstone and the ongoing wolf reintroduction in Colorado (Ripple and Beschta 2004). Hunting remains the most popular and effective deer management strategy, even though they only make up roughly 4.3% of the US population (as estimated in 2015; Hewitt 2015). The effective contribution of hunters in WTD management hinges on their access to hunting grounds.

The availability of hunting land in New England varies by location, posing unique challenges and opportunities for effective WTD management through hunting. In urban areas, hunting opportunities are typically limited due to safety restrictions; however, there are instances where expansive public lands (e.g., national and state forests, parks, and game reserves) offer accessible options (Knoche and Lupi 2012, Wszola et al. 2020). In rural regions characterized by extensive private lands, particularly agricultural landscapes, hunting opportunities tend to be more abundant (Ribot and Peluso 2003, Knoche and Lupi 2007). Nevertheless, accessing these hunting terrains can be challenging due to a range of factors, including landowner regulations and the imposition of prohibitively high hunting lease fees (Mehmood et al. 2003, Zhang et al. 2004). Given that the majority of land in the US is privately owned (Winkler and Warnke 2013), and private lands encompass a substantial portion of WTD habitats (Nagy-Reis et al. 2019), fostering public-private collaborations and facilitating hunter access are key in the effectiveness of hunting as a tool for controlling WTD populations. Initiatives like "Open Fields" programs actively facilitate public access to hunting on private lands across the US by enabling public-private partnerships and sometimes offering incentives to landowners to allow access (Wszola et al. 2020). In addition to improving the efficacy of hunting in controlling local deer, these advancements can also generate substantial economic advantages for local communities, as demonstrated in Knoche and Lupi's (2012) study that estimated an annual contribution of $80 million to Michigan communities from open hunting access. However, benefits such as these may diminish as hunting access is decreasing in New England (O'Shea 2009*a*).

Access to hunting grounds in New England has become increasingly limited, hindering the ability of hunters in successfully controlling WTD populations (Storm et al. 2007, Kilgore et al. 2008, Recce 2008, O'Shea 2009*a*, Williams et al. 2012, Weckel and Rockwell 2013). In Massachusetts, pending bylaws could restrict hunting access by requiring hunters to seek landowner permission, which differs from the traditional system allowing access without permission (O'Shea 2009). This scarcity of accessible hunting areas may result in only localized hunting impacts as deer learn to seek shelter in *de facto* refuges where hunting is not allowed

(Thomas and Adams 1985, Ribot and Peluso 2003, Storm et al. 2007). Concurrently, there has been a steady decline in the American hunter population, further complicating the prospect of effective hunting controls on WTD populations (Brinkman et al. 2007, Conlin et al. 2009, Winkler and Warnke 2013, Hewitt 2015). Some hypothesized reasons behind this decline include reduced access to hunting grounds (O'Shea 2009*a*), different population dynamics resulting in less interest in hunting (Winkler and Warnke 2013), and controversial management implementation reducing participation (Van Deelen et al. 2010, Winkler and Warnke 2013). This decline is expected to persist due to low recruitment rates and an aging hunter demographic (Riley et al. 2003, Tack et al. 2018), prompting questions about the long-term viability of hunting as a management strategy. This shift in dynamics challenges the historic reliance of the American WTD management systems on high hunter participation and ample land access (Ryel 1968, Conlin et al. 2009, Kelly 2018), casting doubts on the future efficacy of hunting in regulating New England's local deer populations.

In this research, I explore the current WTD management paradigms in the Northeastern US (henceforth "New England"), which I refer to as the New England WTD management system or landscape. I define the New England region as including Maine, Vermont, New Hampshire, Massachusetts, Connecticut, Rhode Island, and additionally, New York. Though New York is not typically associated with this region, I include it due to its central position in this research and its implications. While the implications of this study may be relevant to other regions in the US, the primary focus is on addressing issues related to New England hunter recruitment and land access. In this study, I question the number of hunters and amount of land access required to make impactful changes to local WTD populations in New England. More broadly, I aim to determine whether communities can attain their social and ecological goals within the current management paradigms characterized by declining hunter recruitment and limited land access. To explore this multifaceted issue, I propose 3 research questions that in turn address the 1. ecological, 2. theoretical, and 3. social dimensions of this complex challenge (Table 1).

I use deer density as a primary metric of interest due to its frequent association with community perceptions and its ability to serve as an index that relates to both social and ecological objectives. Through my ecological research question, I inquire about the relationship between hunter and deer density in New England. Its linked objective is to analyze the impact of variable hunter density in 11 New England focal towns through an agent-based model analysis. I hypothesize that hunter density is negatively correlated with deer density due to hunting mortality effects. With the theory-based question, I seek to glean insights regarding the relationship between hunter density and the amount of hunting land access required to maintain local deer populations at 0% growth. My objective is to evaluate land access dynamics in 11 New England focal towns through an agent-based model analysis. I hypothesize that the land access requirement to stabilize local deer is negatively correlated with hunter density due to increased harvest opportunities. Through my social science question, I explore the relationship between community support of hunting and the efficacy of this historic deer management strategy in reducing local deer densities. My objective is to assess social drivers behind hunting efficacy and their influences on management outcomes through an agent-based model analysis. I hypothesize that community support of hunting is positively correlated with the efficacy of hunting due to enabling variables such as opening land access.

Table 1. This table depicts the research questions and their corresponding objectives, hypotheses, and predictions.

	Question 1	**Question 2**	**Question 3**
Categories	Ecological Science	Theory	Social Science
Questions	What is the relationship between WTD density and hunter density in New England based on a case study agent-based model analysis of 11 focal towns?	What is the relationship between hunting land access required to maintain the local WTD population at 0% growth and hunter density based on a case study agent-based model analysis of 11 New England focal towns?	What is the relationship between community support of hunting its efficacy in reducing local WTD density in New England based on a case study agent-based model analysis of 11 focal towns?
Objectives	Analyze impact of variable hunter density on local WTD density in 11 New England focal towns through agent-based model analysis.	Evaluate land access dynamics in 11 New England focal towns through agent-based model analysis.	Assess social drivers behind hunting efficacy and their influences on management outcomes through agent-based model analysis.
Hypotheses	H_1. Hunter density is negatively correlated with WTD density due to hunting mortality effects.	H_2. Land access requirements to maintain WTD populations at 0% annual growth are negatively correlated with hunter density due to increased harvest opportunities.	H_3. Community support of hunting is positively correlated with the efficacy of this management strategy due to enabling variables (e.g., opening land access).
Predictions	P_1: WTD density decreases as hunter density increases.	P_2: Land access requirements decrease as hunter density increases.	P_3: As community support increases, hunting's efficacy also increases.

2.3. Methods

2.3.1. Study Area—The broader research team of social and ecological scientists from the University of Wisconsin-Madison, Boston University, Texas A&M University, and Colorado

State University strategically selected 11 focal towns, distributed across the states of New York (NY) (*n* = 5) and Massachusetts (MA) (*n* = 6) (Figure 2) to serve as the foundational basis for

a)

b)

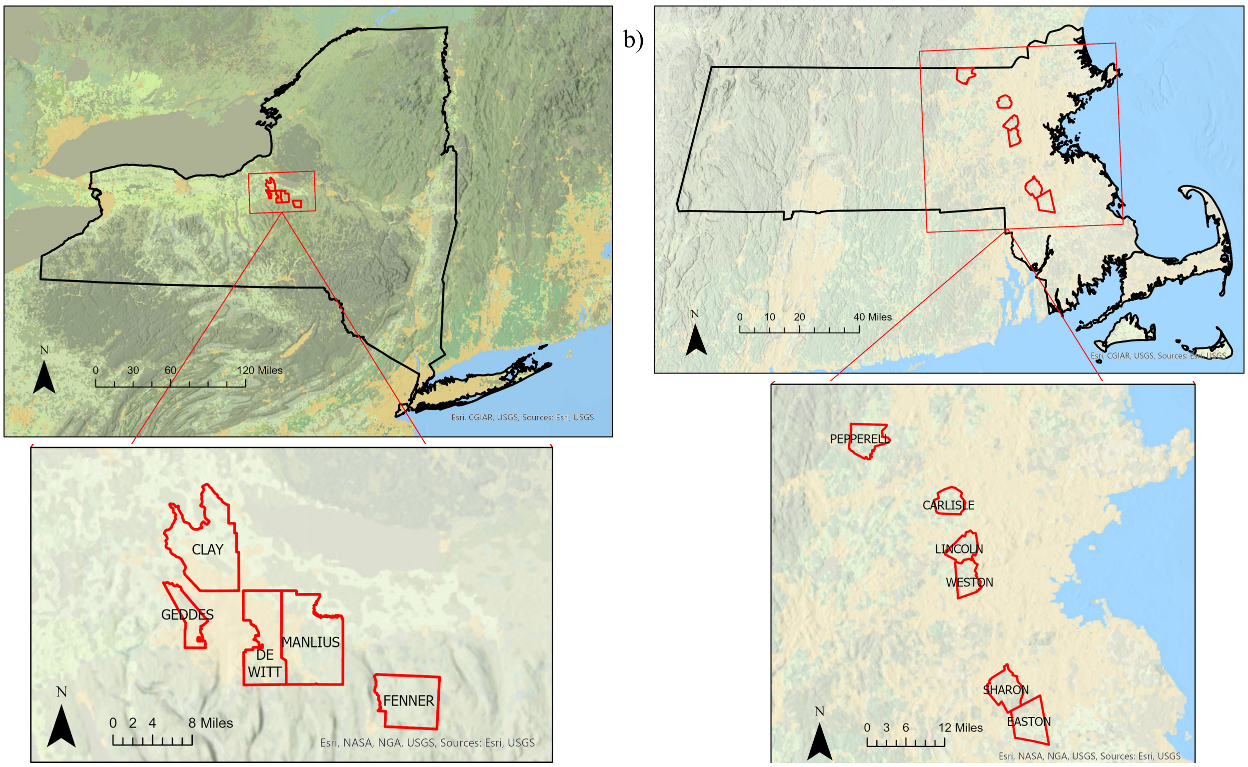


Figure 2. A geographical representation of the study's focal towns (boundaries in red) in (a) New York (*n* = 5) and (b) Massachusetts (*n* = 6), USA. Underlying images sourced from the National Land Cover Dataset (NLCD 2019).

evaluating factors within this intertwined natural-human system. The decision to select these towns was guided by preliminary surveys and extensive consultations with state wildlife agencies, specifically MassWildlife (MA) and the New York State Department of Environmental Conservation (NYSDEC; NY). This selection process was driven by the objective of striking a balance between maximizing the representation of diverse WTD management strategies while adhering to time and budget constraints. This approach added a layer of uniqueness and novelty as broad-scale social-ecological investigations such at this are rare in the literature (Callahan 1984, Franklin 1989, Mirtl and Krauze 2007, Lindenmayer et al. 2012, Dinca et al. 2018).

Although the primary land cover in both states is similar, distinctions in land use allowed for the exploration of hunting and land access under various smaller-scale conditions that mirror other regions in the US (NLCD 2019). Both states share comparable climate and vegetation characteristics (PRISM 2020, NLCD 2019) and exhibit well-documented controversies surrounding locally overabundant WTD populations and their management (Diefenbach and Shea 2011). Both NY and MA have experienced varying levels of success in managing local deer with hunting (Mass.gov n.d., NYSDEC n.d., Decker and Connelly 1990, McDonald et al. 2007, McShea 2012). MA predominantly relies on volunteer bow hunts for WTD management (Dizard and Goble 1995, McDonald et al. 2007, Leaver 2012, Pratt 2015), while NY employs a wider array of hunting and trapping techniques such as shotgun, archery, and primitive firearm seasons (NYSDEC n.d., Lauber and Brown 2000). Compared to NY, MA in particular faces challenges with hunting efforts given a high level of setbacks, land closures, and bylaws restricting hunting access (Mass.gov n.d., O'Shea 2009*a*). Urban development in both states has also decreased the land available for hunting (Larson et al. 2013, MassAudubon 2020). For this project, I examine towns that represent a range of hunting land access levels and hunter densities (Table 2) to increase the likelihood of uncovering meaningful patterns (Tuzlukov 2002) within this diverse management system. Geddes and DeWitt, NY, are the only towns without hunting implementation.

2.3.2. Data Collection—Over a span of 4 years (2019 to 2023), the broader research team collected annual data regarding hunting and land access among the focal towns. To capture diverse perspectives and insights, they deployed web-based surveys to all municipalities in NY

Table 2. MA (*n* = 6) and NY (*n* = 5) focal towns with hunter density and lad access estimates, landscape contexts (suburban vs. rural) and WTD management notes (consideration and implementation of management).

State	Towns	Hunter Density Estimate (#/mi^2)	Hunting Land Access Estimate (% of Town)	Context	Management Notes
MA	Pepperell	25.0	20.65	Rural	• Pepperell does not have a WTD management plan.
	Carlisle	11.0	10.2	Suburban	• Carlisle adopted a volunteer bow hunt program in 2018 but suspended it in 2020 due to controversy.
	Lincoln	14.8	6.0		• Lincoln has not adopted a program but has considered increasing hunting access.
	Weston	14.5	11.3		• Weston has had a bow hunt program on town lands since 2012 and facilitates hunter access on private lands.
	Sharon	17.2	18.0		• Sharon is mostly closed to hunting and has high WTD numbers.
	Easton	3.5	25.8		• Easton is mostly open to hunting with few restrictions.
NY	Fenner	6.0	63.9	Rural	• Fenner does not have a WTD management plan.
	Manlius	3.7	33.2	Suburban	• Manlius adopted a maintenance sharpshooting program in 2018, though a village within the town started the program in 2016.
	DeWitt	0.0	0.0		• DeWitt initiated a sharpshooter program in 2017.
	Geddes	0.0	0.0		• Geddes implemented a sharpshooting program in 2022 in the village of Solvay and has conducted resident surveys regarding local WTD.
	Clay	3.2	21.0		• Clay does not have a WTD management plan.

(n = 994) and MA (n = 351). They designed these surveys to assess stakeholder perceptions of hunting and hunting land access, relevant areas of concern, and the spectrum of WTD management strategies that were under consideration, in progress, or had been abandoned. Furthermore, the research team conducted semi-structured interviews, incorporating both walking and sedentary formats, with randomly selected individuals representing landowners and state agencies such as the MA Department of Conservation and Recreation, Trustees for Reservations, NYSDEC, Westchester County Parks, and Central New York Land Trust. These interviews revealed stakeholder perspectives on hunting land access (what is desired versus how much is available), human-WTD interactions, and their preferences regarding WTD management approaches (Evans and Jones 2011). In addition, hunters were actively involved in the data collection process through the use of "diaries" provided to them during the hunting season by the study team. These diaries served as documentation tools for hunters to record information such as the age and sex of observed and harvested deer, general hunting locations, and their overall satisfaction with their hunting experiences. (McArthur and Baron 1983, Goertz 2006, Strijker et al. 2020)

I used geospatial information from the National Land Cover Database (NLCD) (NLCD, MRLC, USGS, https://www.mrcl.gov/, accessed 2019), legal harvest setback data from the Microsoft Housing Footprint database (Goethlich 2023), and WTD harvest and density estimates from state agencies. In April of 2023, I met with managers in the study area to enhance the accuracy of model landscapes. This involved visiting each focal town and meeting with state wildlife representatives to validate and fine-tune model interpretations. For model parameterization, I primarily relied on estimates from state wildlife agencies, with any gaps filled with estimates from relevant literature and expert (professional in the field with 20+ years of experience) opinion. To promote clarity for US WTD managers, I adopted imperial units (e.g., # deer/mi^2) opposed to metric units in this study (Kelly and Ray 2019).

2.3.3. Agent-Based Models—In the context of agent-based modeling, an "agent" is an autonomous, decision-making entity that interacts with its environment and other agents to produce emergent behaviors (Bonabeau 2002, Heppenstall and Crooks 2012, Salinas et al. 2015, Wilensky and Rand 2015, Marshall 2016). The purpose of agent-based modeling is to address specific research questions and inform a deeper understanding of complex systems (Tang and Bennett 2010, Rand et al. 2011, DeAngelis and Grimm 2014, Tierney 2015, Wilensky and Rand 2015). Rather than perfectly simulating actual systems, their goal is to stimulate thinking and capture phenomena of interest relevant to the research questions (Resnick 1994). In a program called NetLogo (Wilensky 1999), I constructed agent-based models by drawing inspiration from similar models in the literature (Xie et al. 1999, Van Buskirk et al. 2021). Spatially explicit models, as used in this chapter, capture spatial details (e.g., urbanization, land cover, open hunting access areas) that define specific places (DeAngelis and Yurek 2016, Bauduin et al. 2019). See Figure 3 for an example of the model interface. For this project, I adhered to the Overview, Design concepts, Details (ODD) protocol for describing agent-based models (Grimm et al. 2006), as updated by Grimm et al. (2010, 2020). This standardized protocol not only promoted the reproducibility of the project but also enhanced the scientific credibility of the model development process and its outcomes (Railsback and Grimm 2019; see Appendix A for a complete model description and below for a summary).

The models represent real towns with varying sizes, ranging from approximately 12.3 mi^2 (31.9 km^2) to 49.9 mi^2 (129.2 km^2), with a resolution of 900 square meters (30 m x 30 m patches). When applicable to the town, the models feature 2 primary agent types: deer and

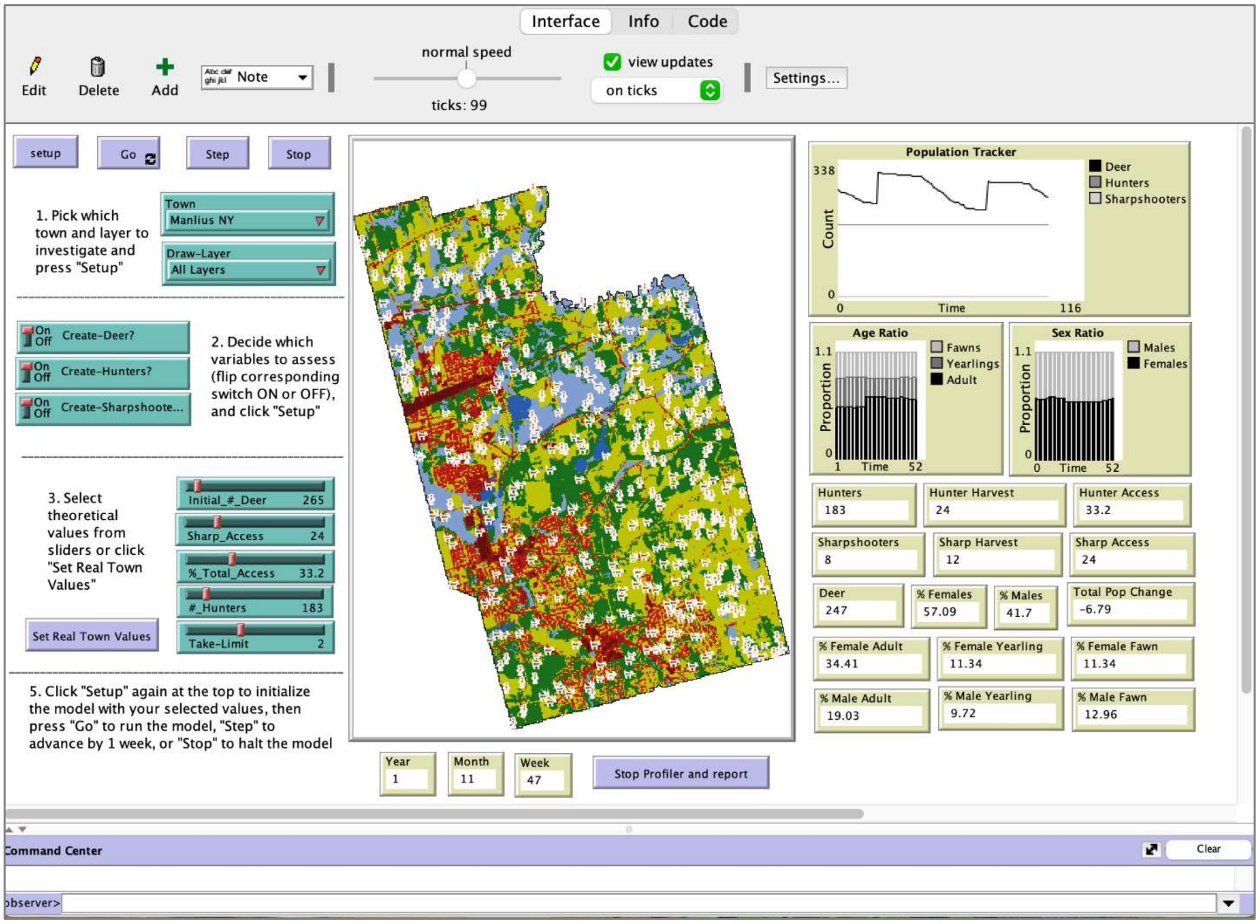


Figure 3. The interface in NetLogo for Manlius, NY, USA, depicting relevant town layers, monitors, graphical outputs, and user controls on the interface (following Wilensky 1999).

hunters, each possessing unique attributes and behaviors that shape their interactions within the distinctive landscapes of each town. Hunters stay in huntable areas and are only active during the hunting season from October through December. Deer are not restricted to any region but only move within their home ranges. Varying based on season and age/sex of the individual deer, home ranges are assigned at initiation of the model or adopted from their mother's when fawns are born. The only time home ranges change is during yearling dispersal when fawns leave their mothers and choose new locations. When deer venture within approximately 0.5 mi/0.8 km of hunters during hunting season, deer are harvested based on estimated probabilities. Refer to

Tables 3-4 for a breakdown of core parameters and sources. This agent-based perspective plays a central role in shaping the emergence of dynamic outcomes.

The model flow consists of 3 phases, where the user 1. sets up the landscape, 2. runs the simulations, and 3. learns from observed outcomes (Figure 4). The setup phase includes creating the landscape and adding agents to the environment (i.e., initialization). The model depicts unique landscapes for each focal town based on imported GIS layers, and the interface selection determines the number of deer and hunters that are present. The run phase includes the movement and interactions of agents based unique rules and programed behaviors. The key components are deer-deer interactions that determine reproduction rates during the rut and hunter-deer interactions that determine harvest rates during the hunting season. The learn phase includes tracking the core output—WTD densities—across contexts to inform results and address the research questions.

The models operate on a weekly time-step starting in January, with simulation runs spanning a 10-year period. During initialization, there are 3 model parameter categories where the user: 1. picks a focal town from 11 options, 2. selects the hunting access level of the town, and 3. chooses high, medium, or low densities for deer and hunters. During the SETUP procedure, the town and access parameter selections inform the model environment, where habitat suitability for deer is calculated based on a project specific habitat suitability index (HSI) that accounts for land cover and use settings (Flemming et al. 2004). Subsequently, deer are placed on the landscape according to the HSI, and hunters are placed in huntable areas. For example, to replicate realistic spatial distributions, deer are more likely to be placed in forests and non-huntable areas than in wetlands and huntable regions. The last phase of this procedure

Table 3. Town-specific parameter breakdown for the agent-based model, depicting values, definitions, and sources.

Town	Pepperell	Lincoln	Carlisle	Weston	Sharon	Easton	Fenner	Manlius	DeWitt	Geddes	Clay
Town Area (mi^2)	23.2	15.0	15.5	17.3	24.2	29.2	31.1	49.9	33.9	12.3	48.9
Hunting Access (%)	20.65	6.03	10.18	11.31	18.00	25.79	63.85	33.22	0.00	0.00	21.00
Hunters (#)	581	222	170	251	416	101	188	183	126	0	155
Hunter Density (#/mi^2)	25.0	14.8	11.0	14.5	17.2	3.5	6.0	3.7	3.7	0.0	3.2
Sharpshooter Density (#/mi^2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.9	3.7	26.0	0.0
Initial Deer (#)	407	504	521	581	731	882	791	1269	862	313	1243
Deer Density (#/mi^2)	17.54	33.60	33.61	33.58	30.21	30.21	25.43	25.43	25.43	25.43	25.43
Harvest Mortality (%)	20	14	14	14	45	45	26	12	9	0	12
Antlerless Harvest Density (#/mi^2)	1.36	1.94	1.94	1.94	5.33	5.33	3.50	1.60	1.27	0.00	1.66
Buck Harvest Density (#/mi^2)	2.24	2.80	2.80	2.80	8.32	8.32	3.09	1.52	0.97	0.00	1.45

Parameter	Definition	Source(s)
Town Area (mi^2)	Areas calculated for each town in GIS.	GIS
Hunting Access (%)	The estimated percent open hunting access for each town, based on state and local setbacks and restrictions.	GIS
Hunters (#)	Hunter number estimate based on licenses sold in each town.	NYSDEC 2019, MassWildlife 2020
Hunter Density (#/mi^2)	Hunter density estimate based on licenses sold in each town.	NYSDEC 2019, MassWildlife 2020
Sharpshooter Density (#/mi^2)	The density of sharpshooters within the available culling areas.	State Wildlife Agency Data
Initial Deer (#)	Deer population estimates based on the most recent state wildlife population reconstruction methods.	NYSDEC 2019, MassWildlife 2020
Deer Density (#/mi^2)	Town-level deer density estimates based on population estimate and town area.	NYSDEC 2019, MassWildlife 2020
Harvest Mortality (%)	Deer harvest mortality according to population and harvest estimates.	NYSDEC 2019, MassWildlife 2020
Antlerless Harvest Density (#/mi^2)	Annual harvest density of antlerless deer (females and fawn males).	NYSDEC 2019, MassWildlife 2020
Buck Harvest Density (#/mi^2)	Annual harvest density of bucks.	NYSDEC 2019, MassWildlife 2020

Table 4. Parameter breakdown for all towns in the agent-based model, depicting parameters, definitions, values, and sources. Harvest and culling parameters do not apply to Geddes or DeWitt, except for hypothetical simulations.

Parameter	Description	Value	Source(s)
% Female Deer	Percent female deer relative to total deer in the population at time of data output (January 1).	58	Coe et al. 1980, Boulanger et al. 2012
% Male Deer	Percent male deer relative to total deer in the population at time of data output (January 1).	42	Coe et al. 1980, Boulanger et al. 2012
% Fawns	Percent fawn deer relative to total deer in the population at time of data output (January 1).	28.75	Collier 2004
% Yearlings	Percent yearling deer relative to total deer in the population at time of data output (January 1).	23.75	Collier 2004
% Adults	Percent adult deer relative to total deer in the population at time of data output (January 1).	47.5	Collier 2004
% Deer Population Growth	Realized deer population growth from annual spring births with hunting present.	30	Norton 2015, Expert Interview
% Fawn Annual Non-Harvest Mortality	The annual non-harvest mortality percent for fawns relative to deer population.	69	Nelson and Mech 1986
% Yearling Annual Non-Harvest Mortality	The annual non-harvest mortality percent for yearlings relative to deer population.	22.5	Nelson and Mech 1986
% Adult Annual Non-Harvest Mortality	The annual non-harvest mortality percent for adults relative to deer population.	22.5	Nelson and Mech 1986
Fawn/Yearling Harvest %	Annual percentage of fawns and yearlings harvested by hunters relative to the total deer population.	10	Boulanger et al. 2012
Adult Harvest %	Annual percentage of adults harvested relative to the total deer population.	90	Boulanger et al. 2012
Buck Harvest %	Annual percentage of bucks harvested relative to the total deer population.	50	Boulanger et al. 2012
Sharpshooter Harvest Density (#/mi^2)	Annual density of deer culled by sharpshooters when implemented, based on most recent average of 3 towns.	11.8	Data from NYSDEC
Sharpshooter Density (#/mi^2)	Sharpshooter density when implemented in each focal town, based on most recent average of 3 towns.	3.88	Data from NYSDEC

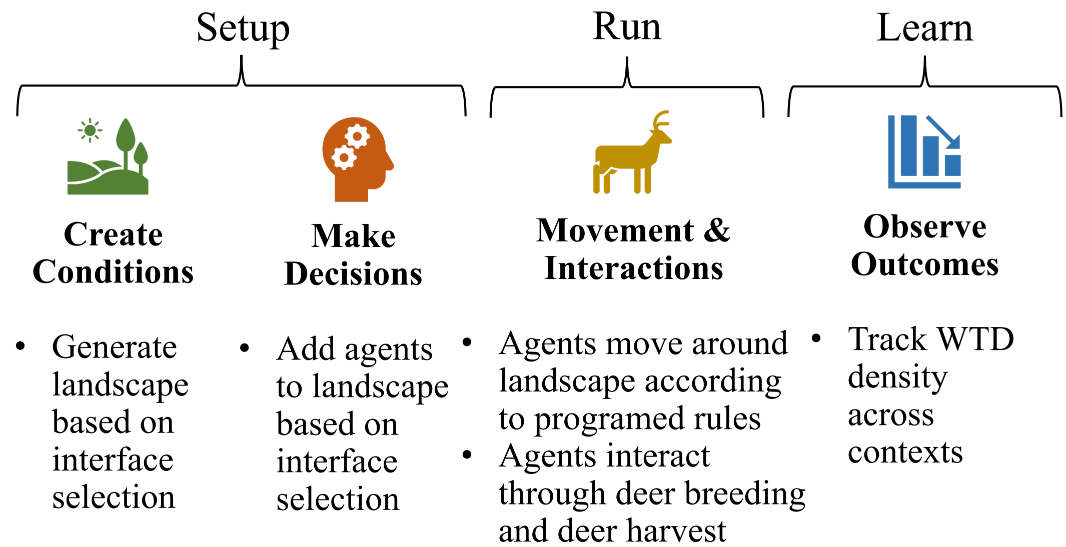


Figure 4. A graphical depiction of the model flow process, including 1) setup, 2) run, and 3) learn phases (Adapted from Monlezun 2022).

includes forming deer social structures in the environment to reflect realistic social dynamics. In the GO procedure, time is tracked, deer are aged, non-harvest mortality occurs, agents move, and deer go through annual behavioral submodels that include a hunting phase (Figure 5). If 10 years has elapsed, the simulation ends. Otherwise, time advances by 1 week and the GO procedure repeats.

I primarily used data from state wildlife agencies to inform model parameterization, supplementing data gaps with insights from experts and relevant literature. I based deer and hunter population estimates on data provided by state wildlife agencies, including harvest-based population reconstructions and hunting license sales (NYSDEC 2019, MassWildlife 2020, NYSDEC 2021). To estimate hunting access, I expanded an existing Geographic Information System (GIS) database that identified potentially huntable lands (i.e., areas that did not fall under

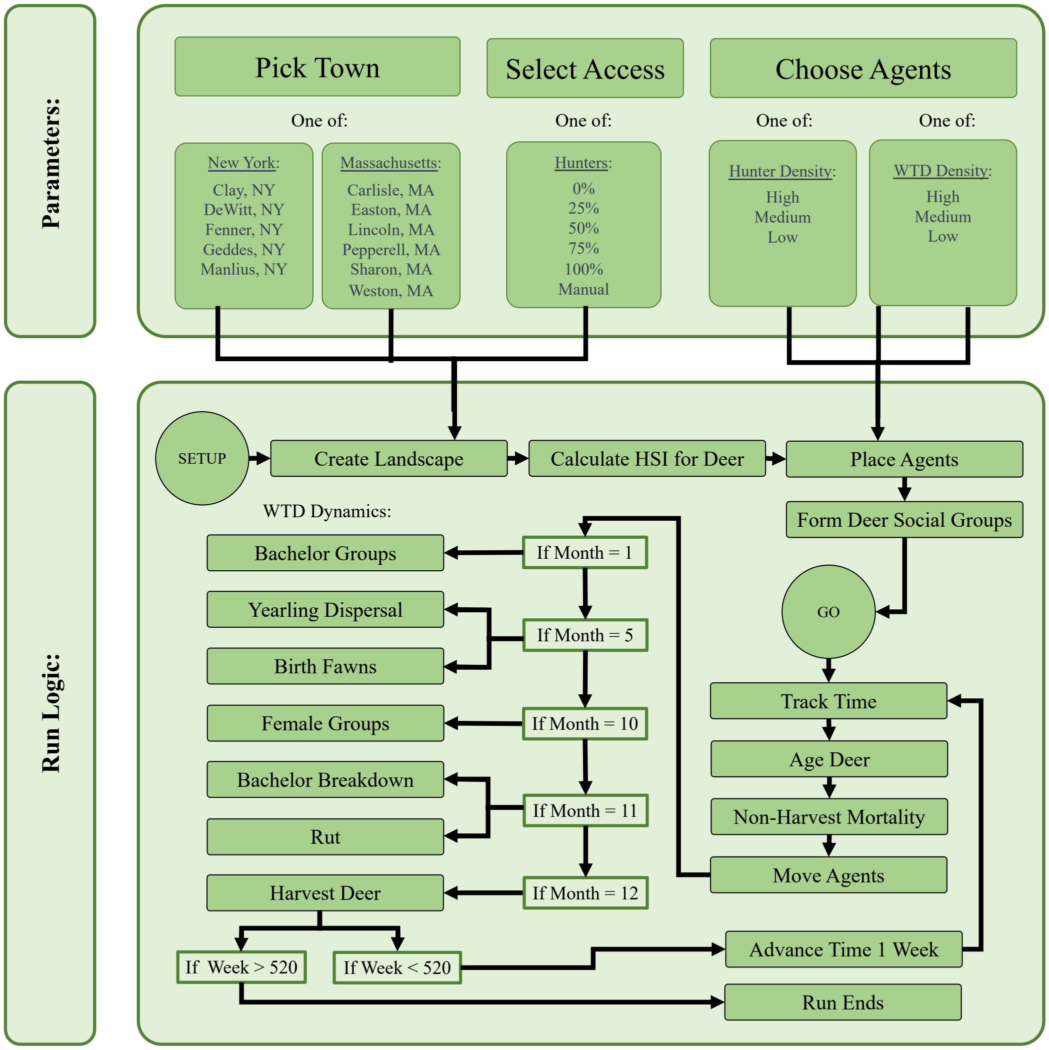


Figure 5. A flow chart diagram of the model processes, including the possible parameter selections and the subsequent run logic (Adapted from Monlezun 2022).

legal setback regulations; Goethlich 2023) by assuming any land without a restriction could be open to hunting.

2.3.4. Scenarios and Analyses—By examining the interplay between variable land access thresholds and hunter densities, I devised unique scenarios for each focal town, as outlined in Table 5 and graphically depicted in Figure 6. To evaluate the potential impact of different levels

Table 5. Scenarios for populating the model (*n* = 198, 18 per town) and sensitivity analysis (*n* = 3). The first column depicts the variable and unit, the second column represents hunter density and hunting access parameters (unique to the town), and the third column provides parameters for the sensitivity analysis. The *Actual* value label indicates the current estimate.

	Hunter Density/ Hunting Access	**Sensitivity Analysis**
Town	11 Focal Towns	Pepperell, MA
# Deer (#/Town)	Actual	Low (203) Medium (407, *Actual*) High (814)
Deer Density (#/mi^2)	Actual	Low (8.8) Medium (17.6 *Actual*) High (35.1)
# Hunters (#/Town)	Low Medium (*Actual*) High	581 (*Actual*)
Hunter Town Density (#/mi^2)	Low Medium (*Actual*) High	25.0 (*Actual*)
Hunter Access (% of Town)	0, 25, 50, 75, 100, Actual	20.6 (*Actual*)

of hunting land access, I systematically tested theoretical thresholds ranging from 0% to 100% of the town area available for hunting in increments of 25% (Figure 7). Specifically, I assessed whether towns could maintain local deer populations (with zero growth) under scenarios of 100%, 75%, 50%, 25%, 0% access, and the actual estimated hunting access percentage for each town. Additionally, I explored the influence of high (double the current estimate), medium (the current estimate), and low (half the current estimates) hunter densities in shaping WTD densities. To derive average outcomes for each scenario, I conducted the standard 30 simulation runs

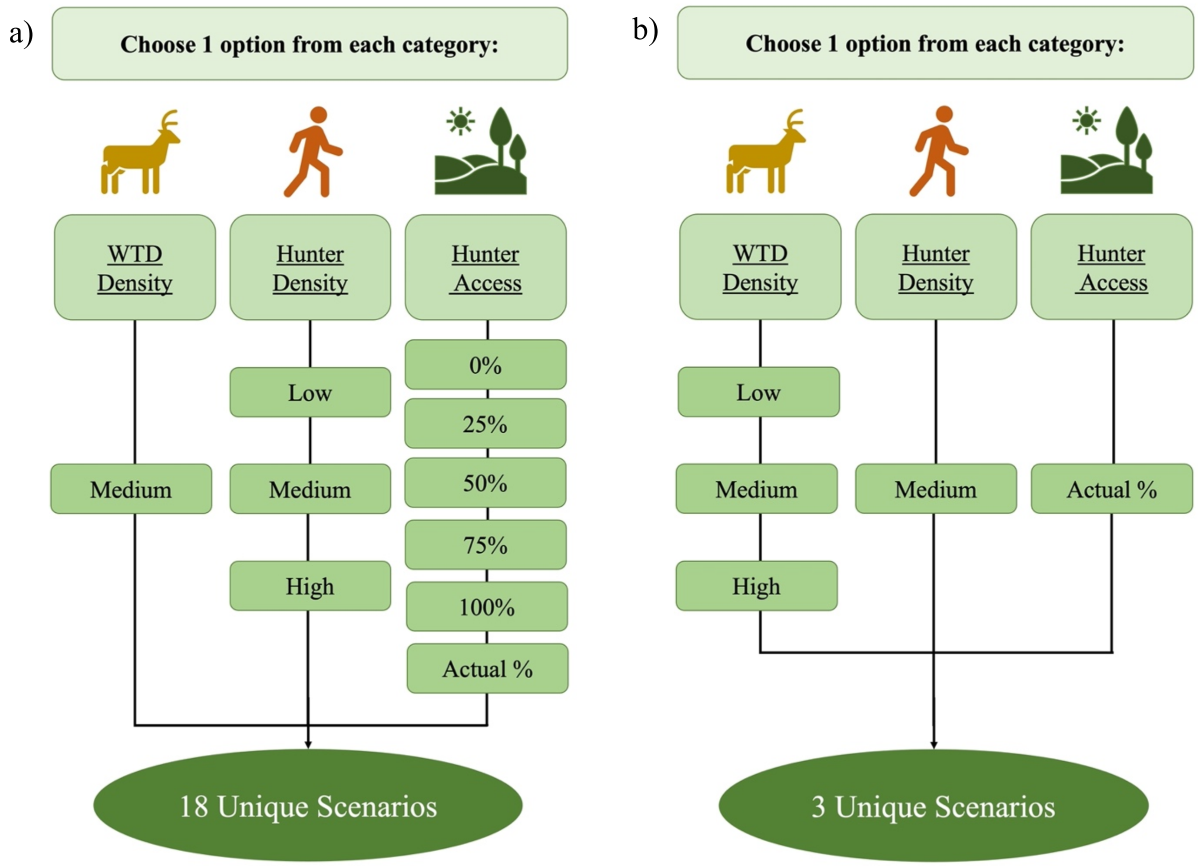


Figure 6. A graphical representation of the possible scenario combinations for the a) collective assessment of all 11 focal towns and b) sensitivity analysis of Pepperell, MA, resulting from parameter selections from categories of WTD density, hunter density, and hunting land access (Adapted from Monlezun 2022).

(Railsback and Grimm 2019), with each run representing a 10-year timeframe. This resulted in 18 unique scenarios per town (*n* = 198) and 5,940 simulation runs for the assessment.

To transfer insights into real-world applications, a defensible connection is necessary between the model environment and the actual system under study (Wilensky and Rand 2015). To promote the model reproducibility of real system phenomena of interest, I employed a variety of techniques such as pattern-oriented-modeling (aligning system properties, mechanisms, and behaviors; Rand et al. 2011), heuristic analysis (rules of thumb; Railsback and Grimm 2019), verification (debugging; Wilensky and Rand 2015, Marshall 2016), and validation (micro-,

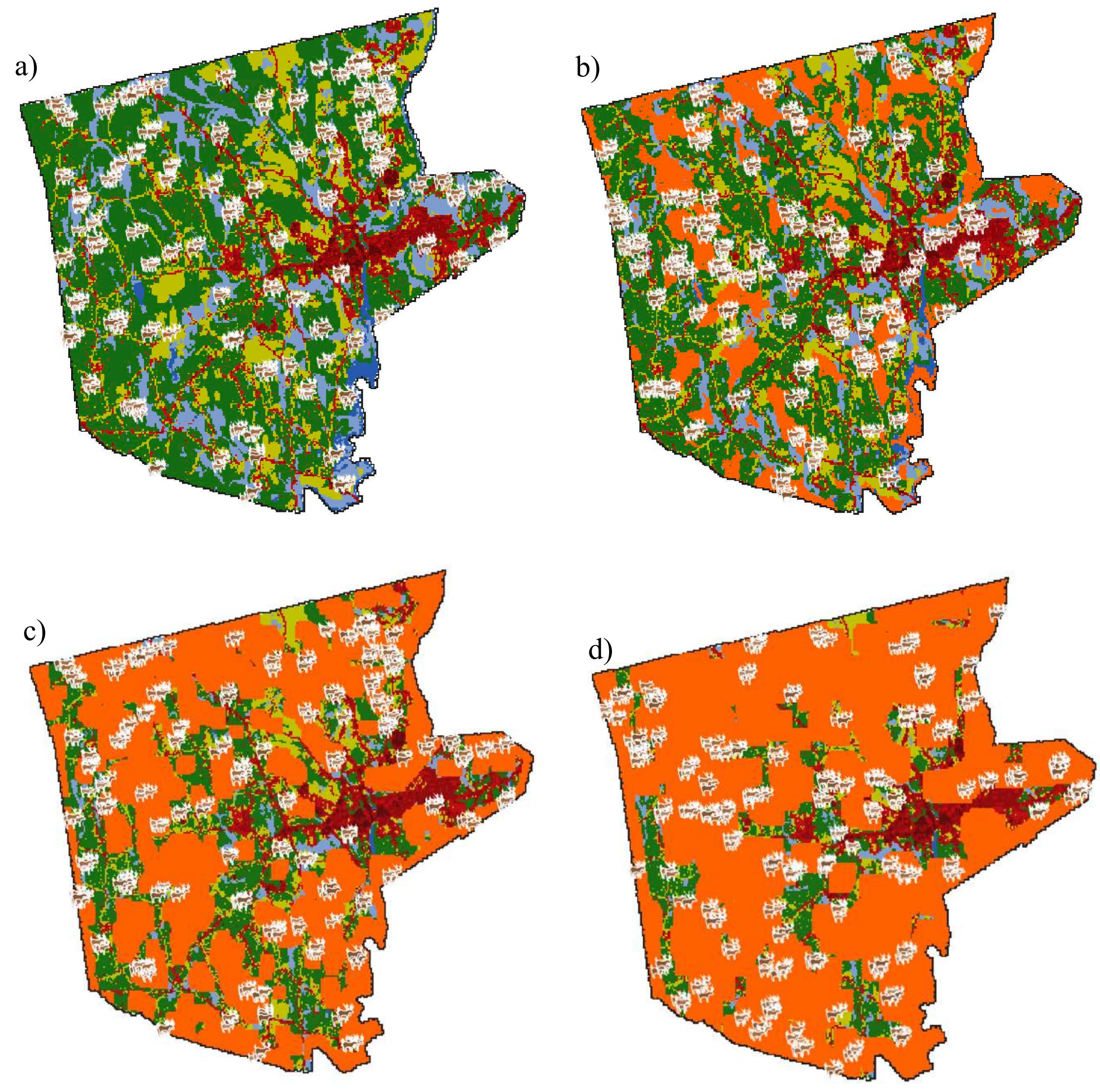


Figure 7. The model landscape for Pepperell, MA, USA, showing theoretical levels of a) 0%, b) 20% (current estimate), c) 50%, and d) 75% of the town land open to hunting access from October through December, represented in orange.

macro-, empirical-, and face-validity; Wilensky and Rand 2015, Marshall 2016). In addition to these methods, I also conducted a formal one-at-a-time sensitivity analysis on Pepperell, MA (representative of average dynamics) to evaluate how changes in key input parameters (i.e., initial deer density) affect results (Table 5, Figure 6). This analysis also addressed Research

Question 1 (ecological) related to ecological science by evaluating the relationship between hunter density and deer density. It included a factorial design, where I systematically altered initial deer density from low (half of the current estimate) to medium (current estimate) to high (double the current estimate) to observe its impact on the outcomes. This logic resulted in 3 unique scenarios and, after using the standard 30 simulation runs (to balance scientific rigor with time feasibility; Wilensky and Rand 2015), 90 simulation runs for the sensitivity analysis.

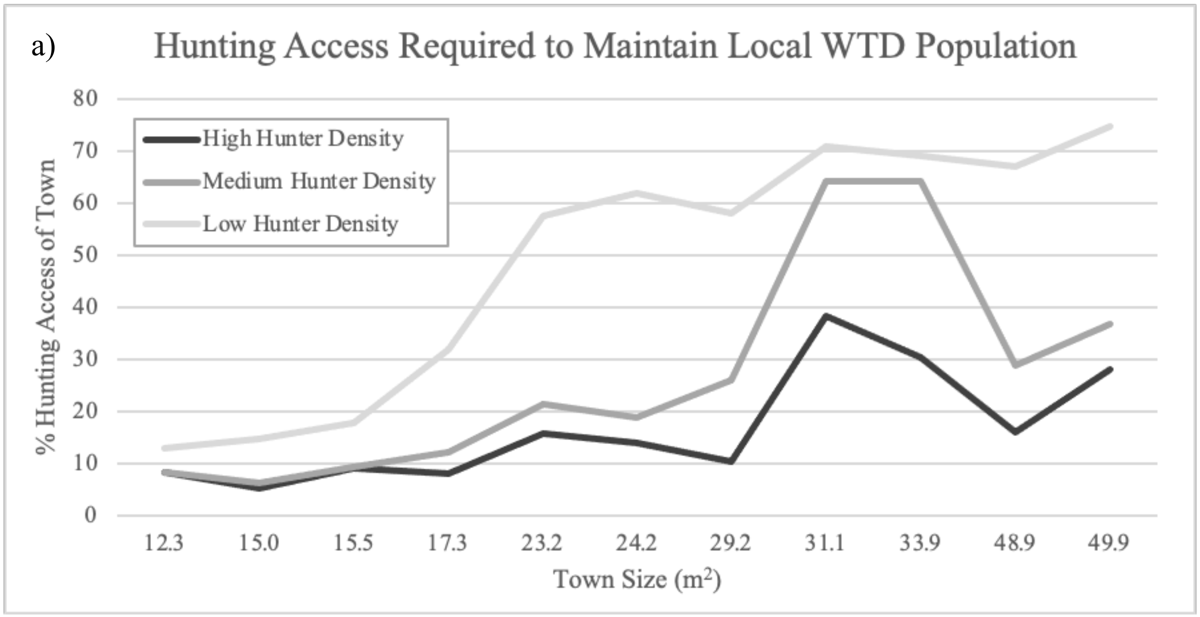
To address Research Question 2 related to access (theory), I created plots for each town to inform a collective chart depicting the relationship between hunter density and the amount of land access required to maintain deer populations at zero annual growth. This 2-part process first involved plotting the percent open access of the town against the percent deer population change after 10 years of consistent management for each hunter density category (low, medium, and high). I then plotted average values from all simulation runs and fitted a trendline to the data. Subsequently, I estimated the x-intercept, which represented the point of inflection for land access where the local deer population did not grow nor shrink—but stabilized. In other words, this point represented the estimated amount of hunting land access required by the town to effectively stabilize their local WTD population with current estimates of deer densities. For the second part of this process, I combined all x-intercept estimates in a box plot to depict the land access requirement for each hunter density estimate.

I addressed Research Question 3 related to social preferences (social) by assessing the relationship between community support and hunting efficacy in controlling local WTD populations. This assessment included a literature review, an evaluation of survey data, and consultations with experts in the field and state wildlife agency representatives. Additionally, I assessed the relationship between town size, hunter density, and the amount of open hunting access required for a town to effectively stabilize local WTD populations. I plotted outcomes as line graphs with trendlines and further investigated whether there were statistically significant differences (paired t-test) between medium hunter density and each of the other hunter density categories (high, low).

2.4. Results

In addition to the results presented below that directly address each research question, I created graphs that assessed the relationship between town size, hunter density, and land access requirements to maintain local WTD populations at zero annual growth (Figure 8). These basic statistics helped to inform the interpretation of the results. I found that the access requirement is positively correlated with town size and negatively correlated with hunter density. In other words, as town size increases, the land access requirement also increases. Larger towns tend to require more extensive access to accommodate the hunting effort needed for maintaining WTD populations, where smaller towns need less access to have the same WTD population effect. Conversely, as hunter density increases, the land access requirement decreases. Compared to current (medium) hunter estimates, towns with higher hunter densities ($t(10) = -3.090$, $p < 0.0001$, t-test) tend to require less hunting land access to effectively manage local deer than towns with low hunter densities ($t(10) = 4.625$, $p < 0.0001$, t-test).

2.4.1. Research Question 1 (Ecological)—The sensitivity analysis demonstrated the negatively correlating relationship between hunter density and WTD density (Figure 9), though the slopes of impact vary based on the initial deer population size and open access level. This analysis reveals that the results are sensitive up to 43.2% with a high initial deer population, and



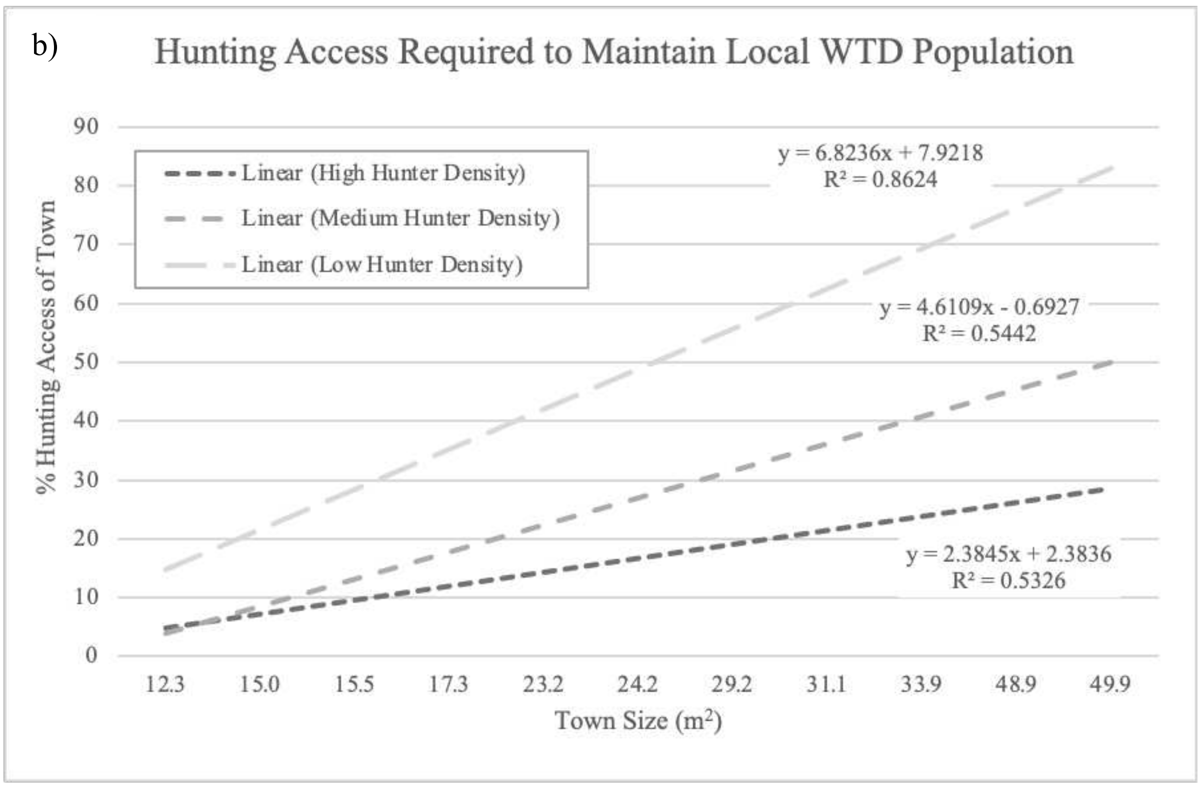


Figure 8. Plotted as a line chart (a) and trendline chart (b), a relationship is depicted between hunter density (#/mi^2), town size (mi^2), and hunting access (% of town) requirement for a municipality to effectively maintain their local WTD population at 0% growth over 10 years of consistent management. As hunter density decreases and town size increases, the requirement of hunting land access increases.

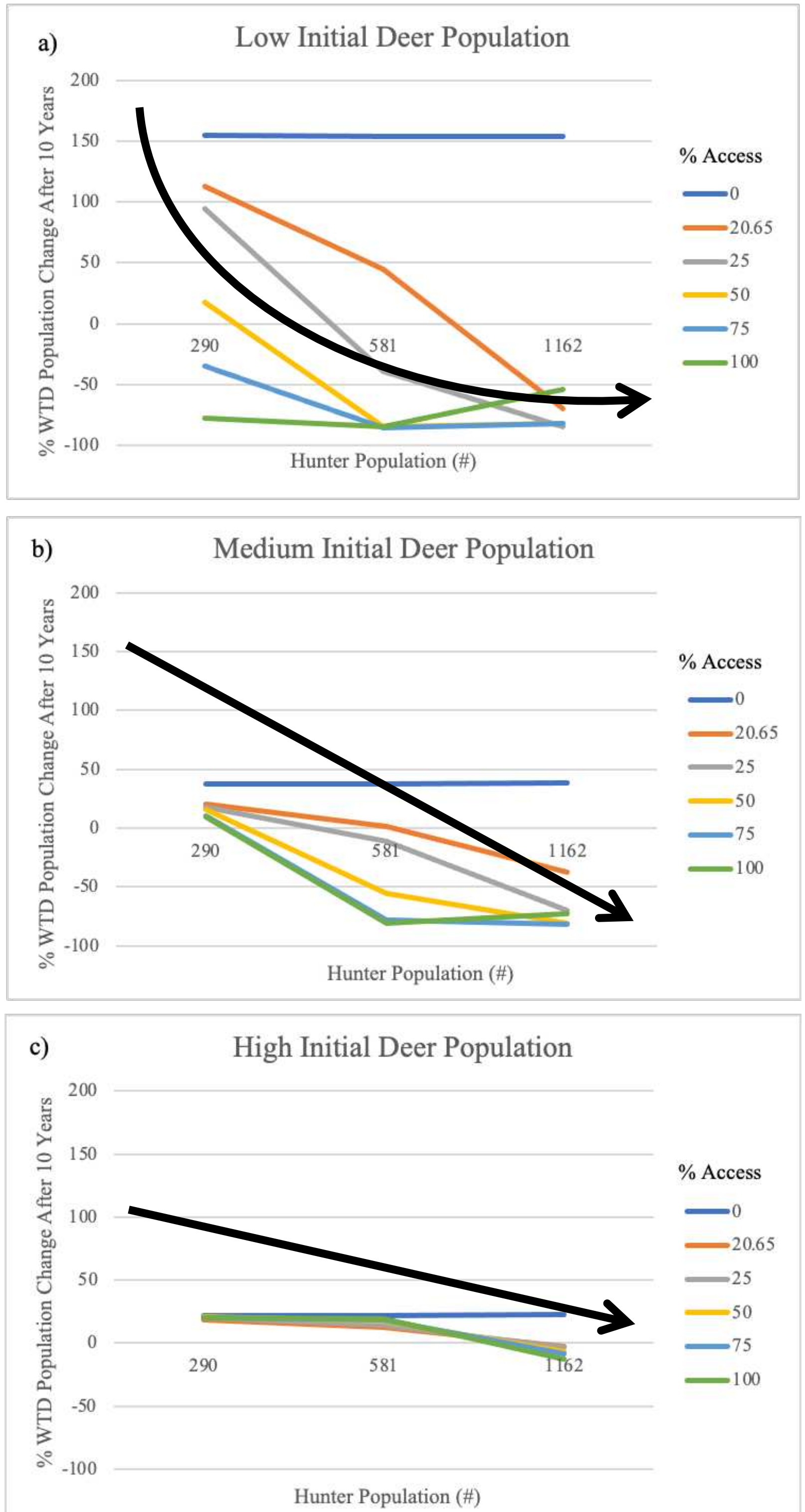


Figure 9. Sensitivity analysis results depicting how changes in the initial deer population changed outcomes from a parabolic (low initial deer) to linear (medium initial deer) to linear with a slope closer to zero (high initial deer) across different hunter densities and land access percentages.

Table 6. One-at-a-time factorial sensitivity analysis results depicting the percent (%) that the outputs fluctuated from the current estimate when a single parameter value was changed.

Variable Changed	*Percent (%) Change of Result from Current Estimate*
Low Initial Deer Population (634)	43.2*
Medium Initial Deer Population (*Current Estimate*, 1269)	0.0
High Initial Deer Population (2538)	-11.6

* Statistical significance

-11.6% sensitive with a low initial deer population (Table 6). The results also depict a higher degree of variability in WTD population change in situations of low initial deer densities (SD: 48.0) compared to medium (SD: 36.4) or high (SD: 12.1). These results indicate that hunter efficacy may be dependent on the initial deer population size. The outcomes demonstrate that different initial WTD population levels result in varying relationships between hunter density and their efficacy. Starting with a low deer population generally resulted in a hyperbolic relationship (Figure 9*a*), suggesting that fewer hunters are required to have a large population reducing effect on the local WTD herd. With a medium initial deer density (current estimate), hunter populations generally exhibited a linear relationship (Figure 9*b*), suggesting that adding hunters to the system generally reduces deer in a ratio of 1:1. Starting with a high initial deer population resulted in a linear relationship with a slope closer to 0 (Figure 9*c*), implying that, despite the level of hunters, WTD populations are relatively hard to manage when they are high.

2.4.2. Research Question 2 (Theoretical)—Plotting average outcomes to identify the x-intercepts (Figure 10) and combining results in a box plot (Figure 11) revealed the negatively correlating relationship between hunter density and the amount of land access required to

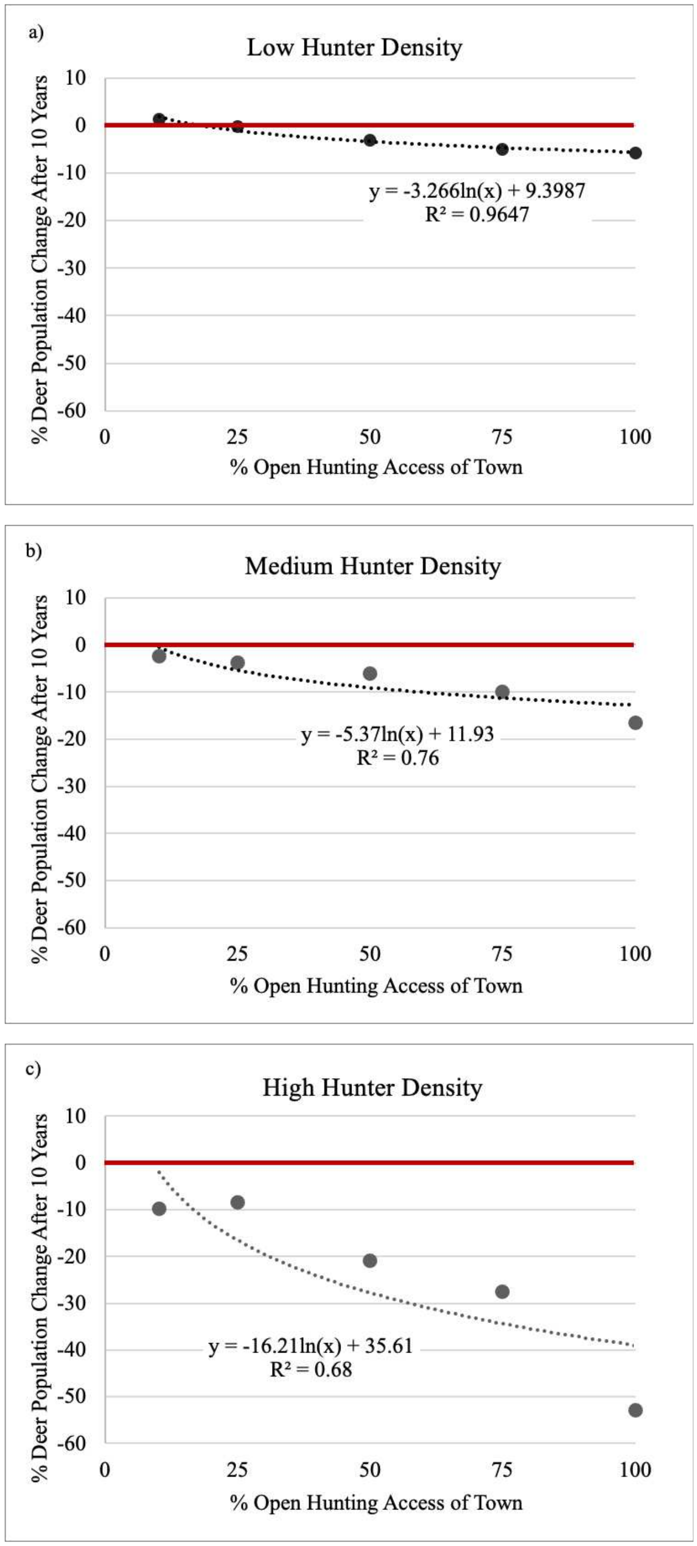


Figure 10. Example plots from Carlisle depicting the percent (%) of land access required (x-axis) to maintain the town deer population (y-axis) under paradigms of a) low (17.8%), b) medium (9.2%), and c) high (9.0%) hunter densities. Red lines indicate zero WTD growth.

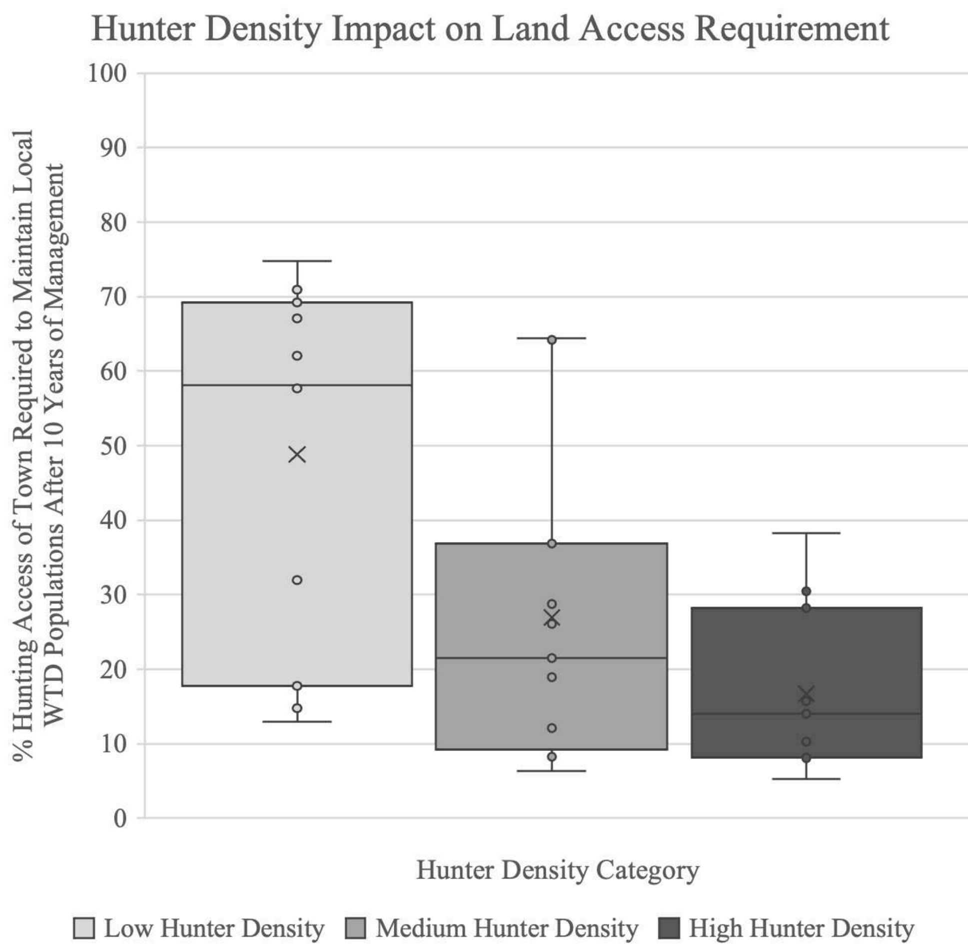


Figure 11. The % hunting land access of towns required to maintain the local WTD population under 3 paradigms of low (SD: 48.0), medium (SD: 36.4), and high (SD: 12.1) hunter densities.

maintain the local deer population at zero annual growth. Detailed accounts of outcomes for each town are provided below and summarized in Table 7.

Carlisle, MA: The model suggests that a low hunter density required approximately 17.8% hunting access in Carlisle to maintain their local WTD population. Medium hunter density requires 9.2% access, and high hunter density requires 9.0% access. Carlisle currently has an estimated hunting access percentage of 10.2%.

Table 7. Percent (%) of town lands required for open hunting access for the town to effectively maintains its local WTD population (0% growth) under paradigms of low, medium, and high hunter densities.

Town	*Town Area (mi²)*	*Current Hunting Access Estimate (% of Town)*	*% Access Requirement with Low Hunter Density (Half of the Current Estimate)*	*% Access Requirement with Medium Hunter Density (Current Estimate)*	*% Access Requirement with High Hunter Density (Double the current estimate)*
Carlisle, MA	15.5	10.2	17.8	9.2	9.0
Easton, MA	29.2	25.8	58.1	26.1	10.3
Lincoln, MA	15.0	6.0	14.8	6.3	5.3
Pepperell, MA	23.2	20.6	57.7	21.5	15.7
Sharon, MA	24.2	18.0	62.1	18.9	14.0
Weston, MA	17.3	11.3	32.0	12.1	8.1
Clay, NY	48.9	21.0	67.1	28.8	16.0
DeWitt, NY	33.9	0.0	69.2	64.2	30.5
Fenner, NY	31.1	63.9	70.9	64.4	38.3
Geddes, NY	12.3	0.0	13.0	8.3	8.2
Manlius, NY	49.9	33.2	74.8	36.9	28.2

Easton, MA: The model estimates that low hunter density requires around 58.1% hunting access for Easton to regulate their local WTD population, where medium hunter density needs 26.1% access, and high hunter density requires 10.3% access. Easton currently has an estimated hunting access level of 25.8%.

Lincoln, MA: Lincoln needs approximately 14.8% hunting access to maintain their local WTD population with low hunter density, 6.3% access for medium hunter density, and 5.3% access for high hunter density. The town's current estimate for hunting access is 6.0%.

Pepperell, MA: For Pepperell, the model suggests that low hunter density required roughly 57.7% hunting access to maintain their local WTD population, where medium hunter density needs 21.5% access, and high hunter density requires 15.7% access. Pepperell currently has an estimated hunting access percentage of 20.7%.

Sharon, MA: Sharon needs about 62.1% hunting access to regulate their local WTD population with low hunter density, 18.9% for medium hunter density, and 14.0% for high hunter density. The town's current hunting access estimate is 18.0%.

Weston, MA: The model indicates that low hunter density requires approximately 32.0% hunting access for Weston to maintain their local WTD population, where medium hunter density needs 12.1% access, and high hunter density requires 8.1% access. Weston currently has an estimated hunting access level of 11.3%.

Clay, NY: Clay needs roughly 67.1% open access to maintain local WTD populations with low hunter density, 28.8% access for medium hunter density, and 16.0 % access for high hunter density. The town's current hunting access estimate is 21.0%.

DeWitt, NY: DeWitt requires around 69.2% hunting access to regulate the local WTD population with low hunter density, 64.2% for medium hunter density, and 30.5% for high hunter density. The town does not currently implement hunting of any kind.

Fenner, NY: For Fenner, the model suggests that low hunter density requires approximately 70.9% hunting access to control the local WTD population, where medium hunter density needs 64.4% access, and high hunter density requires 38.3% access. Fenner currently has an estimated hunting access percentage of 63.9%.

Geddes, NY: Geddes needs about 13.0% hunting access to regulate their local WTD population with low hunter density, 8.3% access for medium hunter density, and 8.2% access for high hunter density. This town does not currently implement hunting of any kind.

Manlius, NY: In Manlius, the model suggests that low hunter density requires around 74.8% hunting access to maintain the local WTD population, where medium hunter density needs 36.9%, and high hunter density requires 28.2%. Manlius currently has an estimated hunting access level of 33.2%.

The model suggests that the current hunter density estimates (medium level) are sufficient to manage local WTD populations for all towns except DeWitt and Geddes, NY (average: 27.0%, maximum: 64.4%, minimum: 6.3%). With a low hunter density, representing half the current estimate, the model results indicate that no towns can maintain their local deer populations, as higher than current access levels are necessary to have the same population effect (average: 48.9%, maximum: 74.8%, minimum: 13.0%). With a high hunter density, representing twice the current estimate, the results suggest that 6 out of 11 (54.5%) towns can effectively control their local WTD population with the currently estimated percent of hunting access available (average: 16.7%, maximum: 38.3%, minimum: 5.3%).

2.4.3. Research Question 3 (Social)—The social assessment revealed the variable relationships between community preferences and the efficacy of hunting in stabilizing local WTD populations. Depending on the context, communities could either support or hinder the efficacy of this management strategy. In towns with a relatively high level of land access and hunter density (e.g., Fenner, NY), successful deer management through hunting is an easier endeavor. Conversely, in towns with limited or no land access and consequently no hunters (e.g., Geddes, NY), the management of local WTD populations presents more challenges.

2.5. Discussion

In this research, I aim to assess the relationships between hunter density, hunting land access, social preferences, and WTD density in New England, where deer density serves as an indicator of hunting efficacy. In this project, I ultimately call into question the sustainability of hunting in New England given declining hunter recruitment and land access levels.

2.5.1. Research Question 1 (Ecological)—The results demonstrate the negative correlation between hunter density and WTD density (Figure 10). As hunter density increases, WTD density decreases, as reflected in the graphs plotting the % WTD population change after 10 years of consistent management. Additionally, as hunter density increases, the R^2 values (explanatory power of the relationships) tend to decrease. Based on model findings, most towns can effectively maintain their local deer populations with medium (current estimate) and high (twice current estimate) hunter densities paired with current hunting access estimates. However, as the number of hunters declines, the capacity of all towns to effectively manage their local deer herds diminishes. This result underscores the critical role hunters play in the effectiveness of this management strategy, as emphasized in previous research (Riley et al. 2003, Conlin et al. 2009, Harper et al. 2012, Winkler and Warnke 2013, Hewitt 2015, Tack et al. 2018). Importantly, the number of hunters required to effectively manage deer is context dependent and varies significantly by municipality. Without enough hunters, municipalities may find it challenging to manage their local WTD populations in alignment with their social and ecological goals, rendering hunting ineffective. These outcomes address my ecological question and support my hypothesis that (H_1) hunter density is negatively correlated with WTD density due to hunting mortality effects.

Furthermore, the sensitivity analysis underscores the dynamic, non-linear nature of this system, demonstrating the variable functional relationship between hunter density and the efficacy of hunting. Depending on the initial deer population, hunters may have a parabolic or linear relationship to hunting efficacy (Figure 9). Understanding these functional relationships is important because they can determine the effort needed by hunters to make impactful WTD population changes and they can influence stakeholder perceptions (Van Deelen and Etter 2003). As the initial deer population increases, hunters may have a harder time managing them regardless of the level of access, as demonstrated by the decreasing variability as deer populations grow (Figure 9). This implies that smaller deer populations are more amenable to manipulation and control, highlighting the enhanced manageability when deer populations fall below a specific threshold (potentially around half of the current estimate), though outcomes are also dependent upon hunter density and accessibility.

2.5.2. Research Question 2 (Theory)—According to the model results, hunter density negatively correlates with the amount of hunting access required to maintain local WTD populations (Figure 11). As hunter density increases, the amount of hunting land access needed to stabilize local deer herds decreases. These results align with the literature for reasons described above, highlighting the importance of hunters in effective WTD management (Riley et al. 2003, Winkler and Warnke 2013, Hewitt 2015), and they are also consistent with the fundamental principles underlying the theory of these systems (Palmer et al. 1997, Ribot and Peluso 2003). It follows logically that a deer's home range would constitute a larger proportion of a smaller town, indicating a higher likelihood of a hunter encountering a deer in such a setting.

Conversely, in larger towns, a deer's home range may not intersect with a hunter's location as frequently, aligning with the observed outcomes. These results further demonstrate the need for tailored management recommendations based on municipality size. These outcomes address my theoretical question and support my hypothesis that (H_2) the level of land access required to stabilize local WTD populations is negatively correlated with hunter density. As hunter density increases, less land access for hunting is needed to effectively control local deer herds.

2.5.3. Research Question 3 (Social)—The model results demonstrate the positive correlation between community support of hunting and its efficacy in controlling local WTD populations. As public support of hunting increases, this strategy becomes more effective in managing local deer herds. Social preferences for hunting and the accessibility of private land play an important role in dictating the effectiveness of hunting in New England. In communities where there is a strong social preference for hunting and a willingness to open private land for hunting purposes, the community is likely to have a more abundant pool of hunters and increased access to huntable areas (Wright and Fesenmaier 1988, Storm et al. 2007, Kilgore et al. 2008, Recce 2008). Conversely, in areas where there is resistance to hunting or limited access to hunting lands, the community may face challenges in recruiting hunters and controlling WTD populations effectively through hunting (Thomas and Adams 1985, O'Shea 2009*a*). Thus, the success of hunting as a WTD management strategy is intricately tied to the social factors of these communities, emphasizing the importance of fostering cooperation and understanding among diverse stakeholder groups to achieve mutually beneficial outcomes for all stakeholder parties (Palmer et al. 1983, Raik et al. 2005, NYSDEC 2018). This result addresses my social question and aligns with my hypothesis that (H_3) community support of hunting is positively correlated with its efficacy due to enabling variables such as greater levels of land access.

2.5.4. Management Recommendations—Based on the model results and the current state of the literature regarding declining hunter recruitment and land access, my broad management recommendations to the collective focal towns are as follows:

1. Population Assessment and Adaptive Strategies:
    a. Base management decision on rigorous data analysis (e.g., historic license sales analysis) while taking into account current trends of declining hunter participation and land access.
    b. Continuously assess and adjust management strategies based on the availability of hunting land access, the recruitment of hunters, the perspectives of stakeholders, and the responses of WTD populations (e.g., regular population surveys).
2. Collaboration and Community Engagement:
    a. Collaborate within and among communities and leverage organizations to optimize hunting land access opportunities (e.g., establish conservation groups).
    b. Engage with the local community to gauge preferences and identify strategies to enhance hunter recruitment and retention (e.g., town hall meetings).
3. Professional Oversight and Efficiency in Operations:
    a. Educate hunters to increase their efficacy in managing local deer populations (e.g., state-funded hunter trainings).
    b. Promote the optimal use of resources and land access through well-informed oversight within well-organized systems (e.g., develop management plans).
4. Alternatives and Incentives:
    a. Explore alternatives (e.g., non-lethal immunocontraception) for effectively managing deer populations in areas where hunting sustainability faces challenges.

b. Develop incentive programs (e.g., reduced hunting fees, offering benefits to private landowners for allowing hunting access) to encourage increased participation and opportunities for hunting land.

2.5.5. Limitations—It's important to stress that the findings of this study should not be interpreted as definitive truths or precise values (Wilensky and Rand 2015). Instead, they should be seen as a platform for stimulating insightful discussions and explorations of this complex system (Railsback and Grimm 2019). For example, when the model suggests that Carlisle may need 17.8% of their town open to hunting for effective management with a low hunter density, this is not an absolute rule but rather a data point for a trend that should prompt consideration (Resnick 1994). The model's outputs represent a tool for igniting dialogue and encouraging critical thinking, compelling us to delve into the reasons behind these specific results and their real-world implications (Resnick 1994, Railsback and Grimm 2019). These findings do not offer a one-size-fits-all solution but rather provided a foundation for exploring the complexities of WTD management in New England (Sterman 2001, Bonabeau 2002). Engaging in such discussions and considering the broader meanings can lead us to more informed, context-specific decisions regarding effective WTD management approaches.

Another important aspect to consider is the reliance on parameter estimates within these models. While these estimates offer the best available approximations, they are not exact measurements of the real system. The data suggests that all towns had relatively stable deer populations over the past 2 decades, with an average of 2% annual growth. Thus, I configured the models to exhibit stable growth under current conditions. The model results indicate that, with the exception of some towns in NY, all towns can sustain their local WTD populations with currently estimated hunter density and land access values. The accuracy of thesse results is contingent on the assumption that the population data was accurate. If the data suggested a higher annual increase in local WTD populations, for example, the outcomes may have differed. Given that these were the most reliable estimates available, I operated under the assumption that all outcomes associated with varying hunter densities accurately represented the dynamics of the local WTD populations. This limitation highlights in the importance of up-to-date population estimates in model endeavors such as these (Wilensky and Rand 2015).

Though these kinds of agent-based models provide unique insights, they should be seen as starting points for discussions and viewed as simplifications of intricate systems (Sterman 2001, Urban 2005, Heard et al. 2014, Wilensky and Rand 2015). As additional monitoring data becomes available, their integration into these models can result in parameter refinement and more dependable outcomes (Xie et al. 1999, Shi et al. 2006, DeAngelis and Yurek 2016). The sensitivity analysis demonstrates the effect that differences in a single variable can have on model results, emphasizing the importance of well-informed model parameterization (Franklin 1989, DelGiudice et al. 2010, Dinca et al. 2018). This iterative process of continuously updating model processes as new data becomes available can yield more realistic and applicable models that better capture the dynamic underpinnings within the New England WTD management system (Mirtl and Krauze 2007).

Because I did not create these models with the intention of them being stand-alone assessments, I omitted various aspects of the actual system from the models to maintain simplicity, comprehensibility, and model functionality (Wilensky and Shargel 2002, DeAngelis and Grimm 2014, Wilensky and Rand 2015). For example, these models represent closed systems and do not account for the dynamic movement of WTD populations, sharpshooters, and hunters in the real world. In reality, there are frequent movement of WTD and hunters across regions, but the models assume that agents are confined to specific towns (Riley et al. 2003, Williams 2008, Lerman et al. 2021). Similarly, the models assume uniform behavior for all types of agents, simplifying the actual system and potentially introducing biases (Railsback and Grimm 2019). The exclusion of these central processes may influence the outcomes, but I deemed their omission necessary to assess the fundamental system dynamics and directly address the research questions.

Acknowledging these limitations led me to implement a range of strategies to enhance the reliability of results. To mitigate these limitations, I established *a priori* criteria for defining model success, adopted a mixed-methods approach (Jick 1997, Strijker et al. 2020), and utilized pattern-oriented modeling techniques to validate the models against observed patterns (Wilensky and Rand 2015, Railsback and Grimm 2019). I also prioritized data sources from recent studies with rigorous designs that were as close to the study area as possible (NYSDEC 2019, MassWildlife 2020, NYSDEC 2021, 2023). Furthermore, I tailored the models to specifically address the research questions, with a primary focus on representing key phenomena of interest (Railsback and Grimm 2019, Grimm et al. 2020).

2.5.6. Significance and Implications—By addressing relevant knowledge gaps, this research contributes to the current understanding of the role of hunters and land access in New England WTD management. The Northeastern US presents a unique blend of urban and rural landscapes, accompanied by evolving ecological and social dynamics, which together pose unique challenges in managing growing deer populations (Mass.gov n.d., Lauber and Brown 2000, Naugle et al. 2002, McDonald et al. 2007, NYSDEC 2007, Berger 2009, O'Shea 2009b, a). The outcomes of this investigation can serve as a resource for wildlife decision-makers, including state wildlife agencies, policymakers, and New England residents. By examining the ecological, theoretical, and social dimensions of hunting efficacy in New England, this study offers a roadmap for crafting adaptive strategies that cater to the changing needs of deer populations and the communities coexisting with them (McArthur and Baron 1983, Conover 1995, Doerr et al. 2001, Goertz 2006, Baggio 2011, Tanner et al. 2014). These insights encourage a proactive approach that upholds ecological equilibriums while addressing societal concerns, ultimately promoting the long-term well-being of human communities and the resident deer of New England.

The implications of this research primarily revolve around providing tailored WTD management recommendations to New England stakeholders. Informed by empirical data and analysis, the recommendations in this chapter can offer WTD management guidance to the focal towns in the study. Whether it involves the implementation of hunter education programs, developing hunter recruitment initiatives, or encouraging private landowners to allow open hunting access, these recommendations present actionable strategies to help balance WTD population management with ecological and social objectives (Ribot and Peluso 2003, Riley et al. 2003, O’Shea 2009, Tack et al. 2018). This study also highlights the importance of considering social dimensions in wildlife management, adding a nuanced layer to existing research that predominantly concentrates on ecological phenomena (Baggio 2011, Levin et al. 2012, Lindenmayer et al. 2012).

Beyond its immediate relevance to New England, this research underscores the broader significance of applying scientific rigor to the evaluation of WTD management systems (Strijker et al. 2020). Wildlife management is a complex balancing act, influenced by various factors, including shifting land use patterns, climate dynamics, and evolving societal attitudes toward management techniques (Chase et al. 2000, Patterson and Power 2002, Raik et al. 2005, Kilpatrick et al. 2011). By subjecting these management systems to rigorous scientific assessments such as agent-based model analyses, we can pave the way for a more systematic and evidence-based approach to wildlife management (Xie et al. 1999, Van Buskirk et al. 2021). This study ultimately contributes to the broader field of wildlife management by demonstrating the usefulness of the agent-based modeling approach in shaping our understanding of interconnected natural-human systems (Turner et al. 1993, Sterman 2001, Urban 2005, Heard et al. 2014). Furthermore, the methodological framework of employing an agent-based perspective in this study can serve as a reference for other regions dealing with similar challenges in managing human-wildlife interactions (Tang and Bennett 2010, DeAngelis and Grimm 2014, Tierney 2015).

2.5.7. Suggestions for Future Research—In the ecological context, agent-based modeling is a promising avenue for deepening our understanding of complex systems, such as hunting efficacy in New England (Sterman 2001). As this approach gains traction in various disciplines, several opportunities for exploration emerge (Turner et al. 1993, Urban 2005, Heppenstall and Crooks 2012, Waldherr and Wijermans 2013, Heard et al. 2014). It is important to address the need for more realistic and intricate models (Railsback and Grimm 2019). Many existing models currently employ oversimplified agent representations, potentially compromising the precision and reliability of their outcomes. By developing more authentic agents and enhancing model analyses, we can produce results that better mirror real-world systems, providing guidance for management decisions such as those surrounding hunting in New England (Wilensky and Rand 2015). Furthermore, the identification and resolution of data gaps, including precise WTD population estimates and hunter densities, represent an important area for future research. Methodologies such as camera trap analysis and surveys of hunters can deliver more dependable estimates to inform model dynamics, ultimately enhancing the reliability and applicability of research outcomes (Felix et al. 2007, Wilensky and Rand 2015).

Related to theory-based research recommendations, assessing the interplay between deer, hunters, and the environment remains of paramount importance for developing well-informed models to address real-world hunting systems (Leong et al. 2009, Baggio 2011, Bruckermann et al. 2021, Roden-Reynolds et al. 2022). As human-wildlife interactions and environmental conditions continue to evolve, the continuous monitoring of these systems is important to promote our current and well-informed understanding. Further exploration in this domain can provide insights into the roles of hunters and land access in managing the growing WTD populations, aiding the development of more effective hunting programs (Brinkman et al. 2007, Storm et al. 2007, Winkler and Warnke 2013). Moreover, additional research in this area can contribute to refining models, offering data-driven support for decision-making and promoting the creation of sustainable WTD management strategies (Tang and Bennett 2010, DeAngelis and Grimm 2014, Van Buskirk et al. 2021).

To complement these ecological and theoretical insights, delving into the social sciences can further enrich our understanding of these coupled natural-human systems (Micklin 1984, Conover et al. 1995, Decker and Chase 1997, Lerman et al. 2021). In-depth investigations into community perspectives on hunting, factors shaping these viewpoints, and variations within and between towns could yield unique insights (Stollkleemann and Welp 2006, Davies and White 2012, Levin et al. 2012, Duda et al. 2021). Exploring the motivations behind hunting and land access choices and examining how these perspectives may intersect or diverge can help lay the foundation for more effective WTD management practices (Decker and Connelly 1990, Hewitt 2015, Kelly 2018). Ultimately, the goal should be to identify solutions that address the multifaceted social and ecological challenges posed by growing rural WTD populations, enabling a sustainable and harmonious coexistence between people and resident wildlife through hunting (McArthur and Baron 1983, Levin et al. 2012).

2.6. Conclusion

This investigation examined the dynamic interplay between hunter density, hunting access, and social factors impacting the efficacy of hunting as a WTD management strategy in New England. My research objectives revolved around exploring the impacts of variable hunter densities and land access levels on hunting efficacy and formulating management recommendations for the focal towns that addressed both ecological and social goals. By using an agent-based modeling approach to study WTD management scenarios for 11 New England Towns, this study has provided unique insights into the complexities of WTD management systems, particularly in the context of hunting in New England.

The model results revealed key insights into the impact of hunter density on land access requirements to sustain effective WTD management in New England. The results indicate that most towns in the region could effectively control their local WTD populations with the current hunter density and hunting access estimates. However, when considering the anticipated declining hunter densities and decreasing hunting access levels, the model suggests that towns may face challenges in maintaining WTD populations within desired limits. The results demonstrate a significant trend between hunter density, town size, and required hunting land access, where larger towns tended to need more hunting access to effectively manage local deer. This emphasizes the need for tailored management approaches and highlighted the importance of hunting land access in effective hunting implementation.

The sensitivity analysis revealed defining connections between hunter density and their effectiveness across various contexts of initial deer populations. With a low initial deer population, a hyperbolic relationship emerges, indicating that a lower hunter density suffices to yield a relatively substantial reduction in WTD populations. Conversely, when the initial deer population matches the current estimates, there is a linear relationship that implied a 1:1 impact of hunters on local WTD population reduction. In the case of a high initial deer population, the model exhibits a linear relationship with a slope closer to 0, signifying that hunters may hava a harder time managing deer when populations are high. These findings underscore the context-dependent nature of the results, highlighting the need for improved data estimation and tailored management recommendations. These findings demonstrate that functional relationships between hunters and deer can change depending on various factors such as the densities of each population, shedding light on potential forthcoming challenges for these communities.

This study underscores the potential challenges that communities in New England may face regarding the sustainability of hunting as a WTD management method due to a declining trend in the US hunter population and diminishing hunting access in the region. It highlights the critical role of hunter density and hunting access in maintaining sustainable WTD populations, emphasizing that the number of hunters and level of access needed to manage local deer effectively vary significantly by municipality. Social preferences for hunting and private land accessibility are influential factors that could either facilitate or hinder the efficacy of hunting. This demonstrates the importance of addressing both ecological and social dimensions of WTD management, emphasizing the need for collaboration and community engagement to achieve mutually beneficial outcomes. The provided management recommendations offer adaptive strategies to balance ecological and social goals and address challenges regarding WTD populations in New England, with potential applicability as a reference for communities facing similar challenges in other regions. This study highlights the necessity of collaborative decision-making and community-based deer management, emphasizing the importance of tailoring management strategies to the unique needs and contexts of each community.

This chapter sets the stage for broader discussions and more extensive explorations of the complex WTD management system in New England. The research findings should be seen not as definitive truths but rather as catalysts for dialogue and critical thinking, offering a solid foundation for investigating the intricacies of WTD management. These insights transcend the focal towns, carrying relevance for WTD management efforts in various regions. While this study primarily focuses on New England, its methodological framework and findings contribute to the broader field of wildlife management. By subjecting management systems to rigorous scientific assessments, such as agent-based model analyses, this research lays the groundwork for a more systematic, evidence-based approach to wildlife management. It underscores the potential of agent-based modeling to enhance our understanding of interconnected natural-human systems. In summary, this chapter represents a single puzzle piece in a larger research endeavor, providing foundational insights into the role of hunter density and hunting access in effective WTD management in New England. It emphasizes the significance of these factors in achieving effective WTD management through hunting in New England. Results provide guidance for focal towns in addressing future challenges and prioritizing investments in strategies aimed at maintaining balanced WTD populations. Through collaborative decision-making and community-based deer management, the provided recommendations encourage towns to promote sustainable human-deer relationships through stakeholder inclusion and engagement. The ongoing development of evidence-based decision-making strategies, fostered by the models in this study, offer a path toward a more sustainable future that harmonizes the coexistence of human communities with resident WTD.

3. WHEN HUNTING ISN'T ENOUGH: THE ROLE OF SHARPSHOOTING IN EFFECTIVE NEW ENGLAND WHITE-TAILED DEER MANAGEMENT

3.1. Summary

This study investigates the effectiveness and feasibility of sharpshooting as a management strategy for urban white-tailed deer (henceforth "WTD") populations in New England. Using a combination of agent-based models, empirical data, and stakeholder analyses, I address the complex ecological, theoretical, and social dimensions of sharpshooting as it relates to urban WTD management in 11 focal towns. The results indicate that most focal towns can currently manage their local WTD populations without the use of sharpshooting. However, with a 25% and 50% reduction in both hunter recruitment and land access, the model demonstrates that between 11.5% and 75.8% (25% reduction), and 21.4% and 81.7% (50% reduction) need to be accessible to sharpshooters to achieve comparable results, suggesting future challenges with feasibility. The stakeholder analysis reveals diverse interests among key groups, emphasizing the importance of community engagement and collaboration in addressing conflicting preferences and implementing effective urban deer management programs. Based on the results, I present social- and ecological-based management recommendations along with suggestions for future research. Sharpshooting should be considered a contingent measure if hunting becomes ineffective. Inclusive sharpshooting programs should promote community involvement and support, and may not be feasible in areas where stakeholders prioritize non-lethal solutions. This research contributes to the understanding of WTD sharpshooting in New England, encouraging science-based, informed urban WTD management approaches and fostering a sustainable future for communities and resident wildlife.

3.2. Introduction

This investigation unfolds in the city centers of the Northeastern US, where the demands of modern conservation intersect with the intricacies of urban wildlife management. In an era marked by the need for sustainable and humane methods of controlling white-tailed deer (*Odocoileus virginianus*, henceforth "WTD" or "deer") populations, professional sharpshooting has emerged as a potential urban management strategy. Sharpshooting refers to the precise and skilled culling of deer by trained professionals (Figura 2017*a*, *b*). This study ventures into uncharted territory by leveraging agent-based model technology to assess the feasibility of urban sharpshooting in the unique context of Northeastern America. By exploring the intricate web of ecological dynamics, human-wildlife interactions, and the ever-evolving conservation landscape, this chapter embarks on a journey to dissect the potential role of sharpshooting in managing this region's urban WTD populations. Through the lens of computational modeling, this research aims to identify the feasibility of this management strategy in the Northeastern US, offering a fresh perspective on a timeless challenge.

In the realm of urban wildlife management, the conservation and control of WTD in the US has long been a subject of paramount importance (Kelly 2018). Through the complex history of WTD management, the preservation and regulation of this iconic wildlife species has undergone considerable transformations. Though the species was historically abundant across the country, unregulated hunting and habitat destruction significantly reduced WTD populations throughout their range, with peak lows in the early 1900s (Heffelfinger et al. 2013). Collaborative management planning among key stakeholders such as government agencies, researchers, and hunting communities resulted in the development of informed, science-based management practices (Chase et al. 2000). Successful restoration efforts, the removal of predators, favorable habitat conditions, and high deer reproduction rates all contributed to the skyrocketing WTD populations we know today (Kelly 2018).

In recent decades, the proliferation of WTD populations in urban areas has caused many stakeholders to view them as overabundant (e.g., perceived to exceed biological and/or social carrying capacity). WTD management has now largely shifted from supporting deer population growth to curtailing it. Recently, urban WTD management has experienced substantial changes through the adoption of strategies like sharpshooting (Williams 2008). Wildlife agencies in some states, in collaboration with landowners, have increasingly integrated sharpshooting into their management plans to address localized overabundance issues in urban settings where hunting is infeasible due to safety restrictions (Doerr et al. 2001). In select urban areas that provide enough of a safety buffer to work within local restrictions, sharpshooting can be carried out by trained professionals. This strategy represents a notable shift in urban WTD management, demonstrating a more adaptive approach that addresses current issues in novel ways (DeNicola et al. 2000, Leong et al. 2009).

Due to the impracticality of hunting in urban settings, urban areas often face challenges associated with an overabundance of WTD, including property damage, landscape disturbances, and elevated risks of disease transmission to both humans and domestic animals (DeNicola et al. 2000, Doerr et al. 2001). Sharpshooting's adaptability to various landscapes, accurate targeting capabilities, and ability to mitigate unwanted consequences of overabundant deer populations contribute to its viability as a potential urban deer management tool (DeNicola et al. 2000, Williams 2008, Hygnstrom et al. 2014). Nighttime sharpshooting is often favored due to reduced human activity, which enhances safety and access to various areas (DeNicola et al. 2000, Droe 2021); however, it necessitates strict safety measures and adequate lighting to ensure precision and humane results (Siemer et al. 2004). The suitability of sharpshooting across contexts not only depends on proper location and timing, but its efficacy is also linked to the scale of effort.

The size of the area for sharpshooting can significantly affect its effectiveness in controlling WTD populations. Larger, well-accessible areas tend to produce more substantial results in population control, especially in locations where extensive land availability allows for precise targeting and population reduction (DeNicola et al. 2000). Conversely, in areas with limited access for sharpshooting, the potential for population-level impact may decrease. The effectiveness of sharpshooting relies on reaching a substantial portion of the target population, and limited access can pose challenges for population reduction due to a deer's tendency to stay within their home range (Peck and Stahl 1997). Consequently, sharpshooting is often observed to have localized rather than population-wide effects (DeNicola et al. 2000, DeNicola and Williams 2008, Figura 2017*a*).

In the backdrop of evaluating sharpshooting efficacy and feasibility in the US, a decline in the number of hunters and hunting land access has raised concerns about the sustainability of hunting in managing local WTD populations (see Chapter 2) (Riley et al. 2003, Winkler and Warnke 2013, Hewitt 2015, Tack et al. 2018). Currently, rural regions may serve as a source of WTD as hunting pressures push them and favorable habitat conditions pull them into urban sink areas (Walters 2001). Lower hunting pressures in rural regions could intensify source-sink dynamics and lead to an even greater influx of deer to urban areas, as more individuals may disperse from the more densely populated rural settings into urban environments (McCoy et al. 2005). With plentiful food and a lack of natural predators, urban areas may continue to serve as a sink, potentially experiencing even higher deer populations (Etter et al. 2002). This underscores the potential need for adaptive and alternative urban deer management strategies, like sharpshooting, to address overabundance in these possible future contexts. However, the possibly of sharpshooting hinges on stakeholders' acceptability of this management method.

The urban WTD management system in the Northeastern US encompasses a complex web of stakeholders, collectively representing a variety of perspectives that shape community decisions surrounding sharpshooting. Among these stakeholders, sharpshooters, landowners, and local residents are key players, substantially influencing the dynamics of this management paradigm (Messmer et al. 1997, DeNicola et al. 2000, *b*, Raik et al. 2005). Some states have professional sharpshooting organizations such as White Buffalo Inc. in New York, a company that specializes in humane urban deer management while prioritizing public safety (White Buffalo Inc. 2020). The success of sharpshooting hinges on their ability to secure access in target areas, demonstrating the critical role of private landowners in contributing to the efficacy of this management strategy. The general public also holds significant influence, as their experiences dictate their beliefs and perspectives, which in turn, drastically shape local sharpshooting feasibility (West and Parkhurst 1973, Stout and Knuth 1995, Siemer et al. 2004, Droe 2021).

Urban deer managers can face substantial challenges in balancing the conflicting preferences of diverse stakeholder groups, particularly regarding the integration of sharpshooting (Feit 1998, Valdez et al. 2006, Bruckermann et al. 2021). This management method has sparked interest and debate within and between communities, with common concerns centered around urban safety and ethics (Figura 2017*a*, Gamborg et al. 2020). These concerns often lead to clear divisions between stakeholder groups that either support or oppose lethal management, where the feasibility of management becomes less relevant when ethics and perceptions of inhumaneness take precedence (DeNicola et al. 2000, Lauber and Knuth 2000, DeNicola and Williams 2008, Droe 2021). Education also plays a role in shaping these viewpoints, with stakeholders more likely to support sharpshooting when informed about its ethical dimensions and potential consequences without its implementation (Stout and Knuth 1995, Lauber and Knuth 2000, Smith 2009).

While some question the ethics behind sharpshooting, others view it as a humane alternative to hunting because trained professionals can achieve higher accuracy when culling deer (Smith 2009). This can promote swift and precise population reductions while minimizing suffering (Droe 2021), in contrast to issues like vehicle collisions, poorly placed hunting shots, disease spread, or other negative effects of overpopulation (e.g., starvation; DeNicola and Williams 2008). Properly conducted sharpshooting aligns with ethical wildlife control principles, prioritizing animal welfare while promoting effective population management (Leopold 1933). Additionally, it can offer social benefits such as local protein donation to food banks, lesser conflicts from deer overabundance, conservation funding, mesopredator control, and economic enhancement (Lauber and Brown 2000, Vercauteren et al. 2011, Duda et al. 2021). Ultimately, the implementation and success of sharpshooting programs heavily rely on community support and acceptance.

The success of sharpshooting in urban deer management hinges on several factors, including community engagement (Raik et al. 2015, Bonney et al. 2016), public education (Smith 2009), clear communication (Siemer et al. 2004, Droe 2021), and ethical adherence (Peck and Stahl 1997, DeNicola et al. 2000, Lauber and Knuth 2000). Implementation is more likely in areas where it is perceived as a suitable solution for local WTD overpopulation issues (Smith 2009, Droe 2021). However, in regions where hunting is both effective and accepted or when communities have limited resources for sharpshooting, hunting or other management methods may be preferred. Public support and cost constraints are significant driving factors (Stout and

Knuth 1995, DeNicola et al. 2000), while land access and hunter density also impact the necessity of sharpshooting (Hewitt 2015). Collaboration between stakeholder groups (West and Parkhurst 1973, Messmer et al. 1997, Chase et al. 2000, Stollkleemann and Welp 2006), accurate population assessments (Chrétien et al. 2016, Gilbertson et al. 2022), well-defined sharpshooter protocols (DeNicola et al. 2000), and policy adjustments (Stout and Knuth 1995, DeNicola et al. 2000) may enhance the efficacy and sustainability of sharpshooting programs. Communities are increasingly seeking science-based evaluations to assess the feasibility of sharpshooting in different urban contexts, aiming to inform a harmonious and enduring solution within a rapidly evolving and intricate system (Stout and Knuth 1995, Droe 2021).

Previous research has shown that sharpshooting can be effective in specific situations, but its overall effectiveness across different contexts and scales remains in question (Droe 2021).This project focuses on the current management of urban WTD populations in the Northeastern US, with potential implications for other regions. In this research, I explore the current WTD management paradigms in the Northeastern US, encompassing Maine, Vermont, New Hampshire, Massachusetts, Connecticut, Rhode Island, and New York. Despite New York not being a conventional part of this region, I include it due to its central role in this study. For simplicity, I henceforth refer to this collective region as "New England". By assessing the effectiveness of sharpshooting in diverse social and ecological settings, I aim to determine its practicality and sustainability in achieving both social and ecological objectives in the region. To address this broad aim, I formulated 3 specific research questions that explore how ecological science, theory, and social science converge to shape WTD sharpshooting dynamics in New England (Table 8).

Table 8. This table depicts the research questions and their corresponding objectives, hypotheses, and predictions.

	Question 1	**Question 2**	**Question 3**
Categories	Ecological Science	Theory	Social Science
Questions	What is the relationship between sharpshooter density and WTD density as evaluated through an agent-based model analysis of 11 New England focal towns?	What is the relationship between sharpshooter access and hunter density/hunting access based on an agent-based model analysis of 11 New England focal towns?	What is the relationship between social preferences and the efficacy of sharpshooting in New England based on a case study analysis of 11 focal towns?
Objectives	Analyze impact of WTD sharpshooting on local WTD density through an agent-based model analysis of 11 New England focal towns.	Evaluate the relationship between sharpshooter access, hunting access, and hunter density in 11 New England focal town agent-based models.	Assess the relationship between social acceptability of sharpshooting and program efficacy through a case study analysis of 11 New England focal towns.
Hypotheses	H_1. Sharpshooter density is negatively correlated with WTD density due to an increased culling presence.	H_2. There is a positive correlation between sharpshooter access, hunting access, and hunter density due to a trade off in harvest effects.	H_3. Stakeholder acceptance of sharpshooting is positively correlated with the efficacy of this management strategy due to enabling factors (e.g., increased access).
Predictions	P_1: As sharpshooter density increases, WTD density decreases.	P_2: As hunter recruitment and hunting land access decrease, the level of sharpshooting access required to maintain local WTD populations will increase.	P_3: As stakeholder acceptance of sharpshooting increases, the efficacy of its implementation also increases.

Through the ecological question, I explore into the relationship between sharpshooter density and WTD density, employing an agent-based model analysis of 11 focal New England towns. I focus on deer density as the key metric of interest because it informs perspectives and subsequent management implementation. I hypothesize a negative correlation between sharpshooter density and WTD density, driven by an amplified culling presence. With the theory-based question, I investigate the relationship between sharpshooter access, hunting access, and hunter density, with the objective of understanding their dynamic interactions. I hypothesize a positive correlation between these factors due to a trade-off in harvest/culling effects. Finally, through my social science question, I inquire about the relationship between social preferences and the efficacy of sharpshooting in New England using a case study analysis of 11 focal towns. I hypothesize a positive correlation between stakeholder acceptance and the efficacy of sharpshooting as a management strategy, dictated by enabling factors such as increased access for sharpshooting implementation. These hypotheses and questions form the foundation for this study as I aim to unravel the multifaceted dynamics of urban WTD sharpshooting within New England's management landscape.

3.3. Methods

3.3.1. Study Area—This project consisted of a larger study team of social and ecological scientists based at the University of Wisconsin-Madison, Boston University, Texas A&M University, and Colorado State University. To broadly evaluate the coupled natural-human system of deer management in the Northeastern US, they strategically selected 11 focal towns in New York (NY) (n = 5) and MA (n = 6), US (Figure 12) based on preliminary surveys and extensive interviews with state wildlife agencies. In NY, deer are managed by the New York State Department of Environmental Conservation (NYSDEC), and in MA, MassWildlife. This selection balanced the diversity of WTD management strategies represented while adhering to the constraints posed by timelines and budgets (Table 9). This approach contributed to the novelty of such a broad-scale social/ecological WTD project in this region as large scale studies

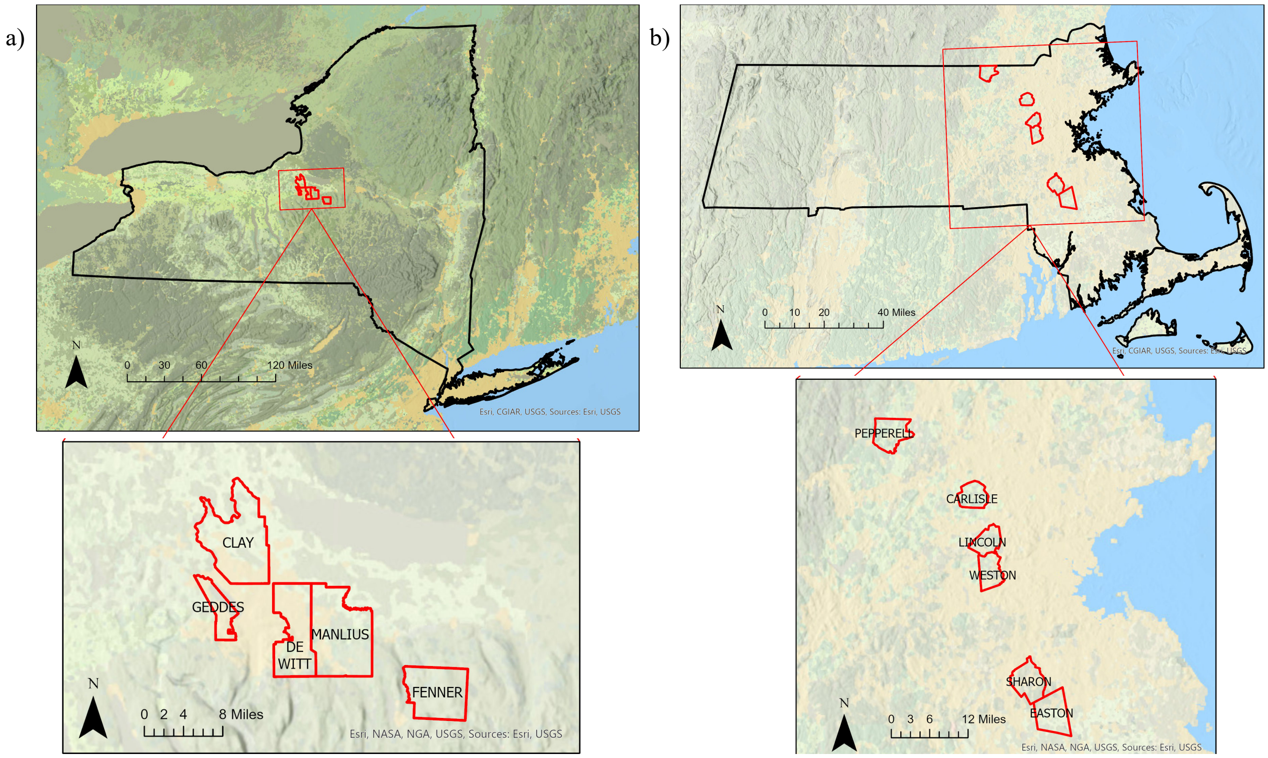


Figure 12. A geographical representation of the study's focal towns (boundaries in red) in (a) New York (n = 5) and (b) Massachusetts (n = 6), US. Underlying images sourced from the National Land Cover Dataset (NLCD 2019).

with extended timeframes are rare in the literature (Callahan 1984, Franklin 1989, Mirtl and Krauze 2007, Lindenmayer et al. 2012, Dinca et al. 2018).

Predominant land cover is largely similar between MA and NY, but differences in land use and urban distributions allowed for the exploration of sharpshooting feasibility and efficacy across contexts (NLCD 2019). Both states share comparable weather and vegetation cover (PRISM 2020, NLCD 2019) and have similar publicized controversies concerning overabundant deer populations and sharpshooting (Diefenbach and Shea 2011). Both NY and MA have experienced varying degrees of success in WTD management programs, and only some towns in NY currently implement sharpshooting (Mass.gov n.d., NYSDEC n.d., Decker and Connelly

Table 9. MA (n = 6) and NY (n = 5) focal towns with landscape context (suburban vs. rural) and WTD management notes (consideration/implementation of management).

State	Towns	Context	Management Notes
MA	Pepperell	Rural	• Pepperell does not have a WTD management plan.
	Carlisle	Suburban	• Carlisle adopted a volunteer bow hunt program in 2018 but suspended it in 2020 due to controversy.
	Lincoln		• Lincoln has not adopted a program but has considered increasing hunting access.
	Weston		• Weston has had a bow hunt program on town lands since 2012 and facilitates hunter access on private lands.
	Sharon		• Sharon is mostly closed to hunting and has high WTD numbers.
	Easton		• Easton is mostly open to hunting with few restrictions.
NY	Fenner	Rural	• Fenner does not have a WTD management plan.
	Manlius	Suburban	• Manlius adopted a maintenance **sharpshooting** program in 2018, though a village within the town started the program in 2016.
	DeWitt		• DeWitt initiated a **sharpshooting** program in 2017.
	Geddes		• Geddes implemented a **sharpshooting** program in 2022 in the village of Solvay and has conducted resident surveys regarding local WTD.
	Clay		• Clay does not have a WTD management plan.

1990, McDonald et al. 2007, McShea 2012). In this project, I analyzed towns where WTD sharpshooting has been considered, implemented, and not considered to increase the likelihood of discovering meaningful patterns (Tuzlukov 2002) in this contrasting management environment.

3.3.2. Data Collection—The broader research team collected sharpshooter-related data annually across 4 years from 2019 to 2023. To capture diverse perspectives and insights regarding stakeholder perceptions of WTD, sharpshooting, and related concerns, the team deployed web-based surveys to all municipalities in NY (n = 994) and MA (n = 351). Additionally, the team conducted semi-structured interviews, both in walking and sedentary styles, with randomly selected individuals representing landowners and state agencies such as the MA Department of Conservation and Recreation, Trustees for Reservations, NYSDEC, Westchester County Parks, and Central New York Land Trust. These interviews were instrumental in exploring the social dimensions of sharpshooting across a range of contexts (Evans and Jones 2011). Furthermore, the research team engaged hunters in the data collection process by providing them with “diaries” during the hunting season. These diaries served as a means for hunters to record various information, including the age and sex of deer observed and harvested, general hunting locations, and their overall satisfaction with their hunting experiences.

I incorporated geospatial data from the National Land Cover Database (NLCD) (NLCD, MRLC, USGS, https://www.mrcl.gov/, accessed 2019), legal harvest setback data from the Microsoft Housing Footprint database, and WTD harvest and density estimates from state agencies (NYSDMV n.d., MassWildlife 2020, NYSDEC 2021). I conducted field work in April 2023 to promote the accuracy of NetLogo landscapes, visiting each focal town and seeking feedback from state wildlife representatives to validate and adjust model interpretations accordingly. I heavily relied on state wildlife agency estimates for model parameterization, filling any gaps with literature estimates and expert (professional in the field with 20+ years of experience) opinion. For clarity to US WTD managers, I largely adopted imperial units (e.g., # deer/mi^2) in this study (Kelly and Ray 2019).

3.3.3. Agent-Based Models—The goal of agent-based modeling is to address specific research inquiries and gain a deeper understanding of outcomes (Wilensky and Rand 2015). This method does not aim to encompass every facet of a phenomenon; rather, it focuses on the exploration of areas of interest, with the intention of stimulating conversation rather than perfectly simulating a system (Resnick 1994). I parameterized and interpreted my models in a program called NetLogo (Wilensky 1999) using similar WTD agent-based models as a foundation (Xie et al. 1999, Van Buskirk et al. 2021). Spatially explicit models, such as the model in this chapter, capture spatial details of places to represent characterizations of specific locations (DeAngelis and Grimm 2014, DeAngelis and Yurek 2016). The models in this chapter visually represented a map of each focal town (Figure 13), depicting realistic urbanization, land

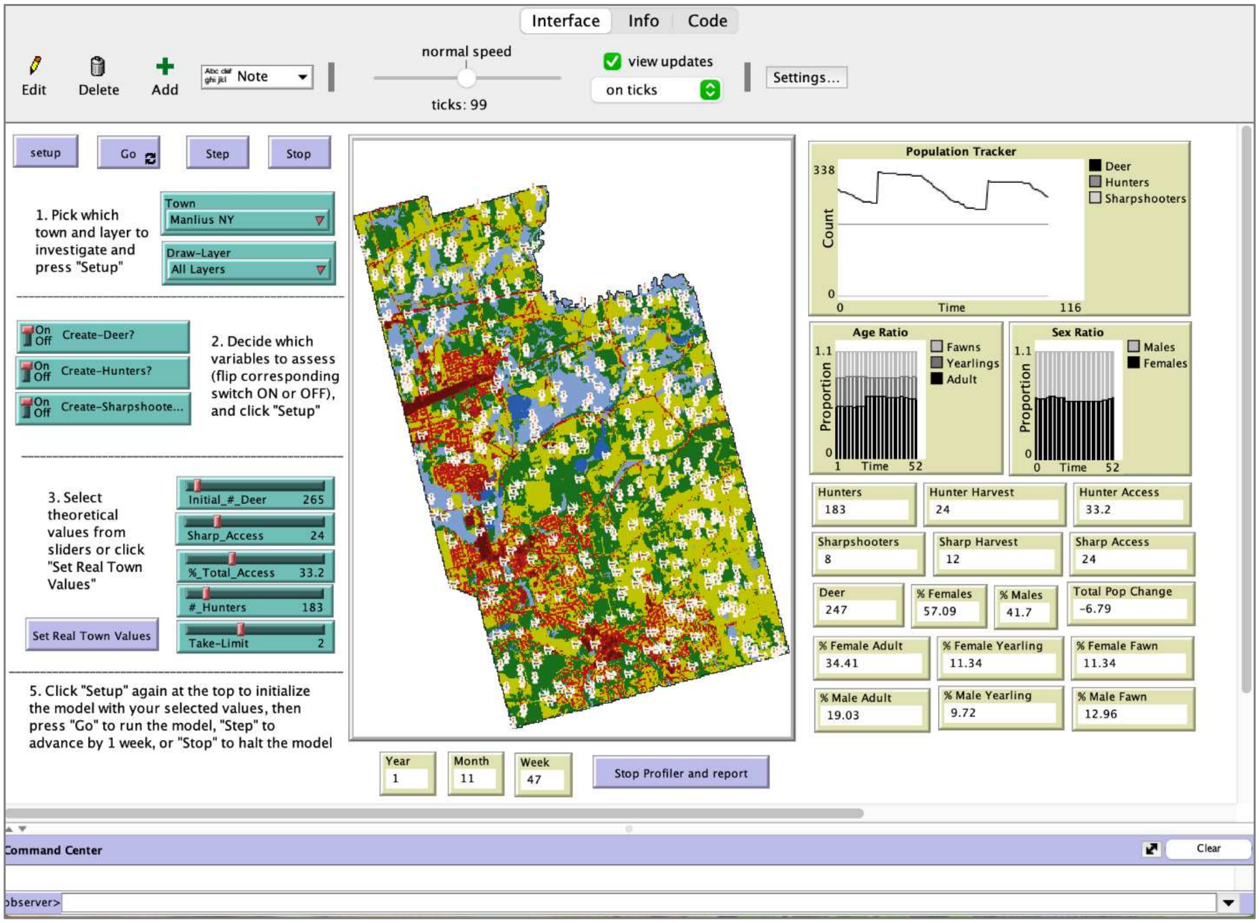


Figure 13. The interface in NetLogo for Manlius, NY, USA, depicting relevant town layers, monitors, graphical outputs, and user controls on the interface (following Wilensky 1999).

cover, and general areas where sharpshooting may occur (Mcintire et al. 2007, Bauduin et al. 2019).

For this project, the overarching purpose of the agent-based model design was to produce insights regarding WTD sharpshooting in real New England towns. Thus, I used an agent-based perspective throughout, where system patterns emerged from interactions between individual deer, hunters, and sharpshooters. In the context of agent-based modeling, an “agent” is an autonomous, decision-making entity that interacts with its environment and other agents to simulate complex systems and emergent behaviors (Wilensky and Rand 2015). I created a model description based on the established ODD (Overview, Design concepts, Details) protocol for describing agent-based models, initially introduced by Grimm et al. (2006) and later updated (Grimm et al. 2010, 2020). The role of this standardized protocol is to promote project reproducibility and strengthen scientific credibility of the model process and outcomes (Wilensky and Rand 2015) (see Appendix B for complete model description and below for a summary).

The models have a resolution of 900 m^2 (30 m x 30 m patches) and represent towns ranging from approximately 12.3 mi^2 (31.9 km^2) to 49.9 mi^2 (129.2 km^2). Operating under a weekly time step (starting in January) and spanning a 10-year period, the models contain 3 agent types (deer, hunters, and sharpshooters) that interact with each other and their shared environment based on distinct attributes and behaviors. During initialization, deer are randomly stratified across the landscape based on a project-specific habitat suitability index (HSI; Flemming et al. 2004) that favors deer placement in more suitable areas (e.g., forest over high development, non-huntable over huntable). Deer move freely year-round within their home ranges, hunters are confined to huntable areas from October through December, and sharpshooters are limited to urban zones from January through March. Home ranges are assigned at initiation based on season and age/sex of the individual deer. Fawns take on the home range of their mother until dispersal when they adopt a new home range. When deer come within specific distances of hunters (approximately 0.5 mi/0.8 km) or sharpshooters (roughly 0.2 mi/0.3 km) during their respective seasons, the deer are harvested in response to estimated probabilities. This agent-based perspective plays a central role in shaping the emergence of dynamic outcomes.

The model flow consists of 3 phases, where the user 1. sets up the landscape, 2. runs the simulations, and 3. Learns from observed outcomes (Figure 14). The landscape is created and

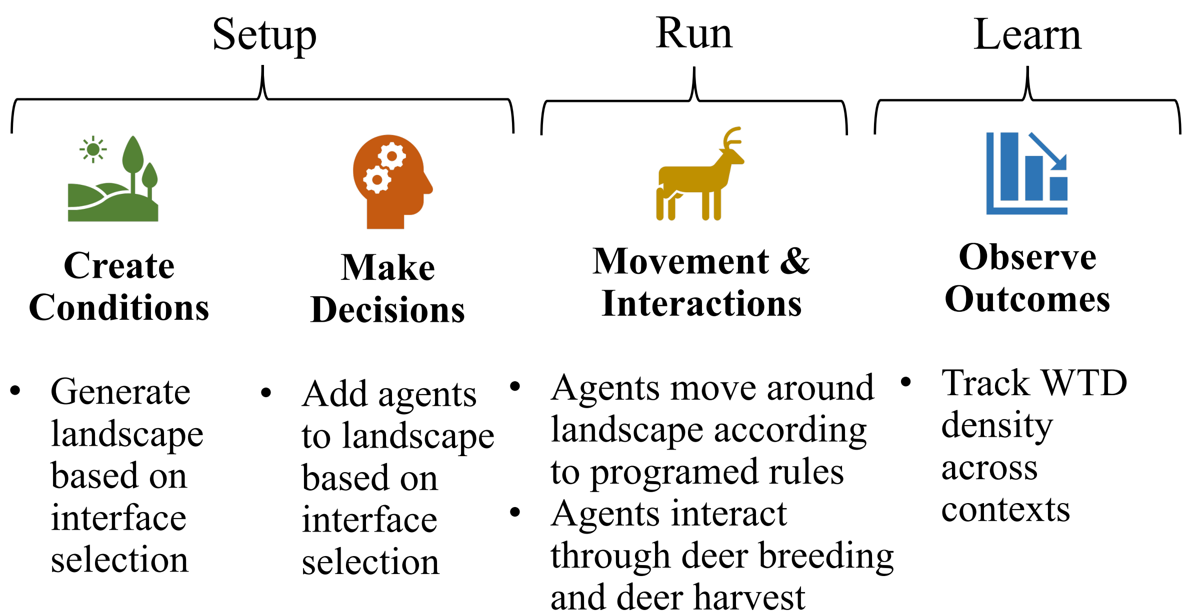


Figure 14. A graphical depiction of the model flow process, including 1**)** setup, 2**)** run, and 3**)** learn phases (Adapted from Monlezun 2022).

agents are placed upon it during initialization of the setup phase. At this point, the model interface depicts a unique landscape of the town selected, showing realistic urban areas where sharpshooting may occur. Similarly, realistic quantities of deer, hunters, and sharpshooters are depicted based unique data for each town. Agents move and interact with each other and their shared environment during the run phase based on agent-specific attributes and behaviors. The key interactions are between deer-deer during the rut (i.e., reproduction rates), hunter-deer during the hunting season (e.g., harvest rates), and sharpshooter-deer during the culling timeframe (e.g., cull rates). WTD density is tracked throughout the simulation, ultimately informing results and addressing research questions during the learn phase of the model process.

During initialization, there are 3 model parameter categories where the user: 1. picks a focal town from 11 options, 2. selects the hunting and sharpshooting access levels of the town, and 3. chooses high, medium, or low densities for deer, hunters, and sharpshooters (Figure 15).

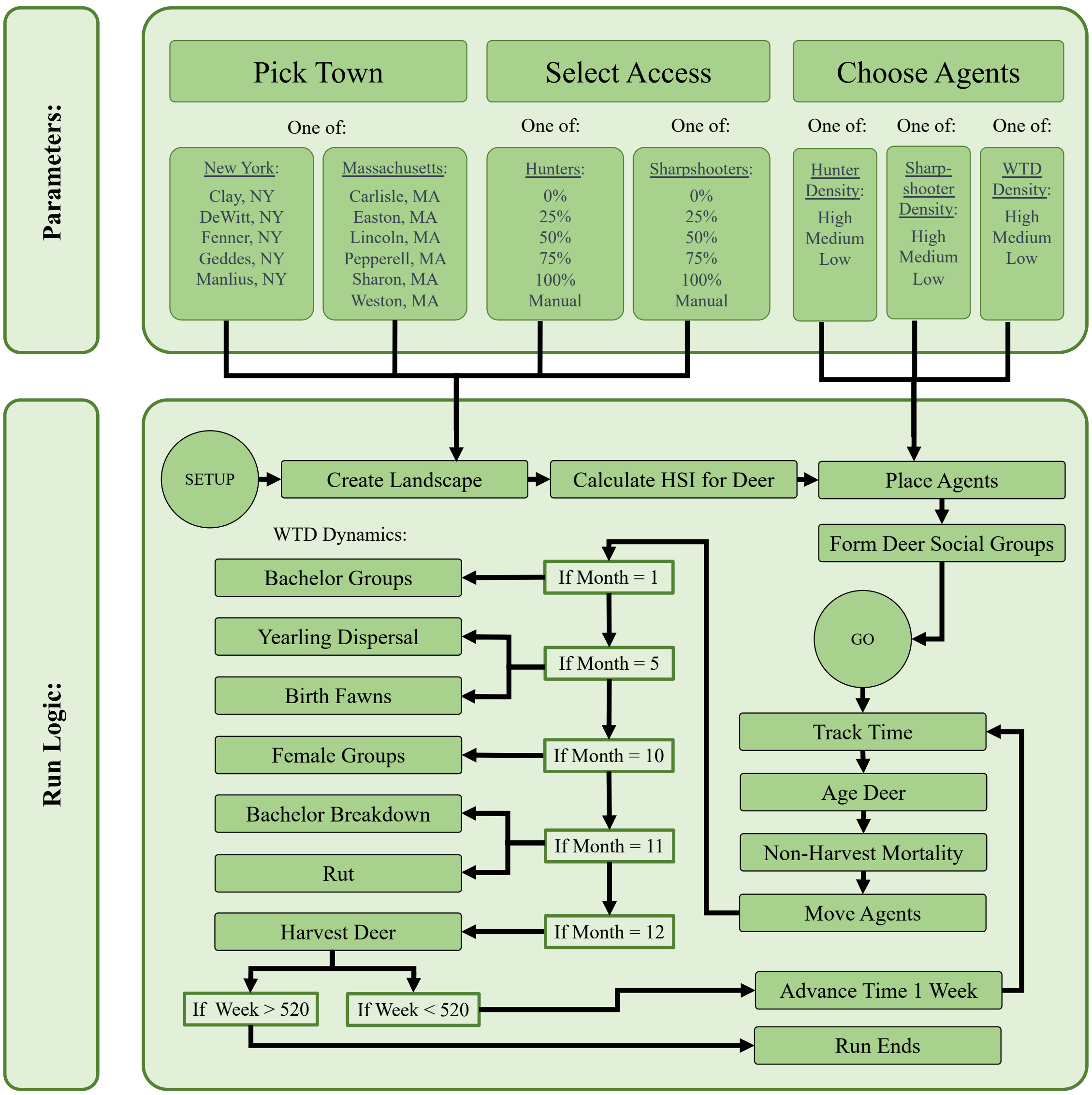


Figure 15. A flow chart diagram of the model processes, including the possible parameter selections and the subsequent run logic (Adapted from Monlezun 2022).

During the SETUP procedure, the town and access parameter selections inform the model environment, where habitat suitability for deer is calculated. Subsequently, deer are placed on the landscape according to the HSI, hunters are placed in huntable regions, and sharpshooters are placed in urban areas. The last phase of this procedure includes forming deer social structures in the environment to reflect realistic social dynamics. In the GO procedure, time is tracked, deer are aged, non-harvest mortality occurs, agents move, and deer go through annual behavioral submodels that include a sharpshooting phase (Figure 15). The simulation ends when 10 years has elapsed, otherwise time advances by 1 week and the GO procedure repeats.

Drawing from data primarily sourced from state wildlife agencies, and filling data gaps with expert opinion and the literature, I initialized all towns based on the most recent estimates of deer, hunter, and sharpshooter densities, along with estimates of land access for hunting and sharpshooting. Refer to Tables 10-11 for a breakdown of core parameters and sources. I estimated current deer and hunter populations per focal town based on state wildlife agency data of harvest-based population reconstructions for deer and licenses sold for hunters. I estimated hunting access in GIS by identifying land that did not fall under legal setbacks or local restrictions (Goethlich 2023) and assuming it could be open for hunting. Based on interviews with state wildlife agency representatives, I estimated sharpshooter densities, access levels, and culling rates in towns that implement this strategy.

3.3.4. Scenarios and Analyses—The towns of Manlius, DeWitt, and Geddes, NY are the only focal towns that currently have sharpshooting incorporated into their WTD management programs. To hypothetically evaluate the potential impact of sharpshooting in towns where this strategy is not currently implemented, I derived sharpshooter parameters from the towns where

Table 10. Town-specific parameter breakdown for the agent-based model, depicting values, definitions, and sources.

Town	Pepperell	Lincoln	Carlisle	Weston	Sharon	Easton	Fenner	Manlius	DeWitt	Geddes	Clay
Town Area (mi^2)	23.2	15.0	15.5	17.3	24.2	29.2	31.1	49.9	33.9	12.3	48.9
Hunting Access (%)	20.65	6.03	10.18	11.31	18.00	25.79	63.85	33.22	0.00	0.00	21.00
Hunters (#)	581	222	170	251	416	101	188	183	126	0	155
Hunter Density (#/mi^2)	25.0	14.8	11.0	14.5	17.2	3.5	6.0	3.7	3.7	0.0	3.2
Sharpshooter Density (#/mi^2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.9	3.7	26.0	0.0
Initial Deer (#)	407	504	521	581	731	882	791	1269	862	313	1243
Deer Density (#/mi^2)	17.54	33.60	33.61	33.58	30.21	30.21	25.43	25.43	25.43	25.43	25.43
Harvest Mortality (%)	20	14	14	14	45	45	26	12	9	0	12
Antlerless Harvest Density (#/mi^2)	1.36	1.94	1.94	1.94	5.33	5.33	3.50	1.60	1.27	0.00	1.66
Buck Harvest Density (#/mi^2)	2.24	2.80	2.80	2.80	8.32	8.32	3.09	1.52	0.97	0.00	1.45

Parameter	Definition	Source(s)
Town Area (mi^2)	Areas calculated for each town in GIS.	GIS
Hunting Access (%)	The estimated percent open hunting access for each town, based on state and local setbacks and restrictions.	GIS
Hunters (#)	Hunter number estimate based on licenses sold in each town.	NYSDEC 2019, MassWildlife 2020
Hunter Density (#/mi^2)	Hunter density estimate based on licenses sold in each town.	NYSDEC 2019, MassWildlife 2020
Sharpshooter Density (#/mi^2)	The density of sharpshooters within the available culling areas.	Data from NYSDEC
Initial Deer (#)	Deer population estimates based on the most recent state wildlife population reconstruction methods.	NYSDEC 2019, MassWildlife 2020
Deer Density (#/mi^2)	Town-level deer density estimates based on population estimate and town area.	NYSDEC 2019, MassWildlife 2020
Harvest Mortality (%)	Deer harvest mortality according to population and harvest estimates.	NYSDEC 2019, MassWildlife 2020
Antlerless Harvest Density (#/mi^2)	Annual harvest density of antlerless deer (females and fawn males).	NYSDEC 2019, MassWildlife 2020
Buck Harvest Density (#/mi^2)	Annual harvest density of bucks.	NYSDEC 2019, MassWildlife 2020

Table 11. Parameter breakdown for all towns in the agent-based model, depicting parameters, definitions, values, and sources. Harvest and culling parameters do not apply to Geddes or DeWitt, except for hypothetical simulations.

Parameter	Description	Value	Source(s)
% Female Deer	Percent female deer relative to total deer in the population at time of data output (January 1).	58	Coe et al. 1980, Boulanger et al. 2012
% Male Deer	Percent male deer relative to total deer in the population at time of data output (January 1).	42	Coe et al. 1980, Boulanger et al. 2012
% Fawns	Percent fawn deer relative to total deer in the population at time of data output (January 1).	28.75	Collier 2004
% Yearlings	Percent yearling deer relative to total deer in the population at time of data output (January 1).	23.75	Collier 2004
% Adults	Percent adult deer relative to total deer in the population at time of data output (January 1).	47.5	Collier 2004
% Deer Population Growth	Realized deer population growth from annual spring births with hunting present.	30	Norton 2015, Expert Interview
% Fawn Annual Non-Harvest Mortality	The annual non-harvest mortality percent for fawns relative to deer population.	69	Nelson and Mech 1986
% Yearling Annual Non-Harvest Mortality	The annual non-harvest mortality percent for yearlings relative to deer population.	22.5	Nelson and Mech 1986
% Adult Annual Non-Harvest Mortality	The annual non-harvest mortality percent for adults relative to deer population.	22.5	Nelson and Mech 1986
Fawn/Yearling Harvest %	Annual percentage of fawns and yearlings harvested by hunters relative to the total deer population.	10	Boulanger et al. 2012
Adult Harvest %	Annual percentage of adults harvested relative to the total deer population.	90	Boulanger et al. 2012
Buck Harvest %	Annual percentage of bucks harvested relative to the total deer population.	50	Boulanger et al. 2012
Sharpshooter Harvest Density (#/mi^2)	Annual density of deer culled by sharpshooters when implemented, based on most recent average of 3 towns.	11.8	Data from NYSDEC
Sharpshooter Density (#/mi^2)	Sharpshooter density when implemented in each focal town, based on most recent average of 3 towns.	3.88	Data from NYSDEC

sharpshooting is practiced. I then applied these statistics to all other focal towns to gauge potential sharpshooting effects. Cross-referencing 11 focal towns with 6 possible sharpshooter access thresholds ranging from 0% to 100% (Table 12, Figure 16), I assessed 6 scenarios per

Table 12. Scenarios for sharpshooting efficacy assessment (*n* = 55) and sensitivity analysis (*n* = 225). The first column depicts the variable and unit, the second column represents sharpshooting efficacy parameters (unique to the town), and the third column provides parameters for the sensitivity analysis.

	Sharpshooting Efficacy	**Sensitivity Analysis**
Town	11 Focal Towns	Manlius, NY
# Deer (#/Town)	Actual	Low (634) Medium (1269, Actual) High (2538)
Deer Density (#/mi²)	Actual	Low (12.7) Medium (25.4, Actual) High (50.9)
# Hunters (#/Town)	Actual	Low (92) Medium (183, Actual) High (366)
Hunter Town Density (#/mi²)	Actual	Low (1.8) Medium (3.7, Actual) High (7.3)
Hunter Access (% of Town)	Actual	0, 25, 50, 75, 100
Sharpshooters (Present)	Yes, No	Yes, No
Sharpshooter Density (#/mi²)	0.7	0.7 (Actual)
Sharpshooter Land Access (% of Town)	0, 25, 50, 75, 100, Actual	Actual

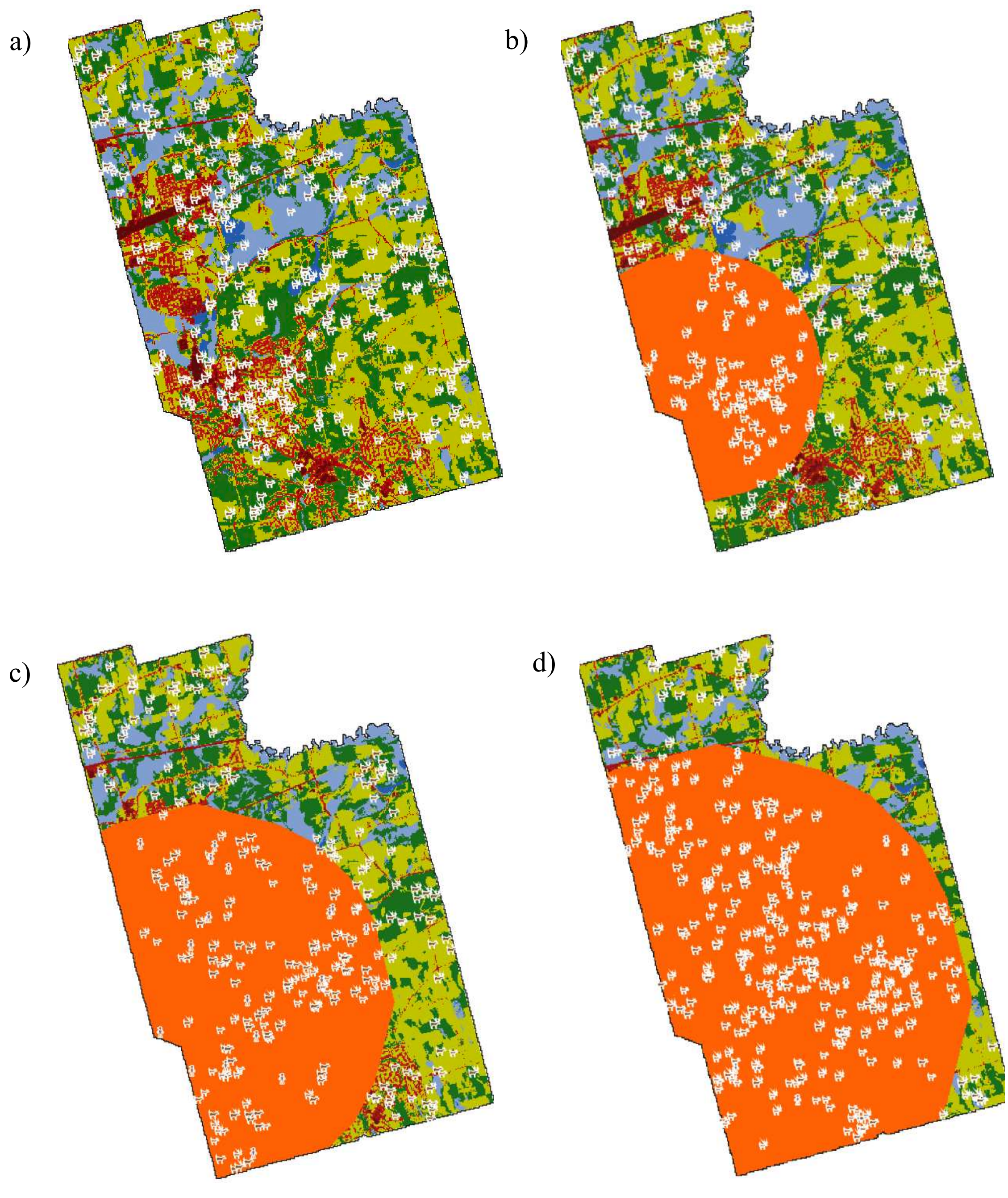


Figure 16. The model landscape in NetLogo (Wilensky 1999) for Manlius, NY, USA, showing theoretical levels of a) 0%, b) 25% (current estimate), c) 50%, and d) 75% of the town land open to sharpshooter access from January through March, originating from the urban center in orange.

town to yield 66 total scenarios (Figure 17). I ran each scenario the standard 30 times (to balance scientific rigor with time feasibility; Wilensky and Rand 2015) to yield 1,980 simulation runs to inform the output.

To address Research Question 1 regarding sharpshooter and deer density (ecological), I plotted average scenario values based on 30 simulation runs for each town comparing sharpshooter density to WTD density after 10 years of consistent management. Because sharpshooter density varies significantly depending on the context and their impact is better assessed by their access level, I used sharpshooter access as an indicator of sharpshooter density. In other words, I maintained a constant sharpshooter density for all scenarios based on the average density of the focal towns with sharpshooting programs. To address Research Question 2 regarding sharpshooter access (theory), I calculated the x-intercept for each graph to estimate the percent sharpshooting access required by each town to maintain local WTD populations at zero growth after 10 years of consistent management. I did this for 3 categories of theoretical hunter density and hunting access levels. The first category represented the current estimate of hunters and hunting access for each town, and the second and third represented estimates of a 25% and 50% reduction in both hunter density and hunting access, respectively. Subsequently, I combined these results in a box plot to assess the sharpshooting access requirement under scenarios of variable hunter recruitment and hunting access.

To transfer insights into real-world applications, a defensible connection is necessary between the model environment and the system under study (Wilensky and Rand 2015). To promote the model replication of real system phenomena of interest, I employed a variety of techniques such as pattern-oriented-modeling (aligning system properties, mechanisms, and

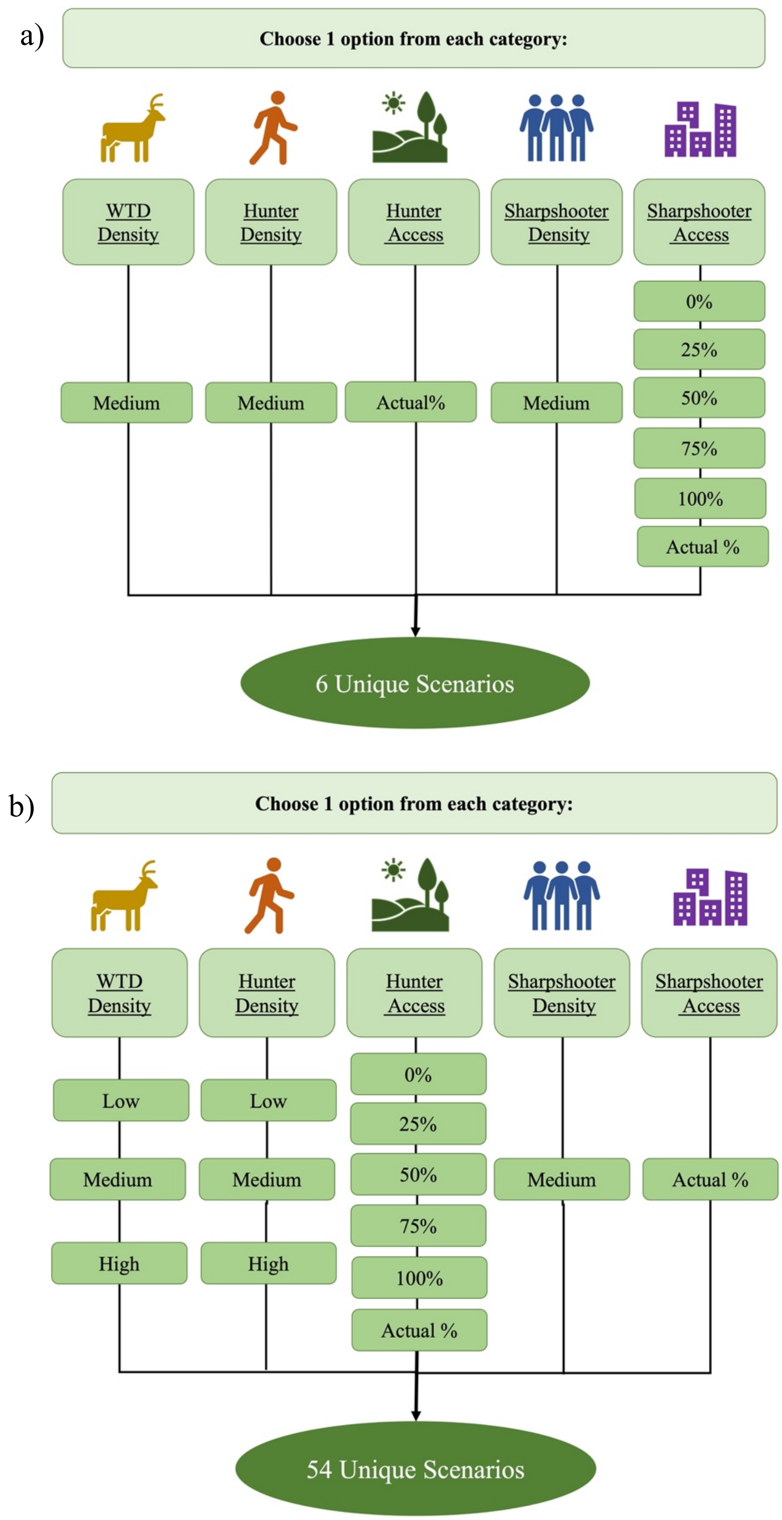


Figure 17. A graphical representation of the possible scenario combinations for the a) collective assessment of all 11 focal towns and b) sensitivity analysis of Manlius, NY, resulting from parameter selections from categories of WTD, hunter, and sharpshooter densities, and hunting and sharpshooting land access (Adapted from Monlezun 2022).

behaviors; Rand et al. 2011), heuristic analysis (rules of thumb; Railsback and Grimm 2019), verification (debugging; Wilensky and Rand 2015, Marshall 2016), and validation (micro-, macro-, empirical-, and face-validity; Wilensky and Rand 2015, Marshall 2016). In addition to these methods, I also conducted a one-at-a-time sensitivity analysis on Manlius, NY due to the well-documented and successful sharpshooting program of this town, making it a reliable representation. For this analysis, I systematically modified 1 variable of interest (initial deer density, hunter density, and hunting access) at a time to observe its impact on the outcomes (Figure 17). For deer and hunters, I analyzed density thresholds of low (half of the current estimate), medium (current estimate), and high (double the current estimate). Because hunting access had more uncertainty, I assessed a range from 0% to 100% in increments of 25% of the town. I also conducted paired, 2-tailed t-tests on each outcome to assess statistically significant differences. This logic resulted in 54 unique scenarios, and when replicated with the standard 30 simulations each (to balance scientific rigor with time feasibility; Wilensky and Rand 2015), yielded 1,620 total simulation runs to inform the sensitivity analysis results.

To address Research Question 3 regarding social preferences (social), I conducted a stakeholder analysis. In this analysis, I examined the social complexities related in WTD sharpshooting and assessed the diverse viewpoints of the groups involved (Raik et al. 2005, Leong et al. 2009). Based on interview and survey data of town representatives, expert opinion, and literature conclusions, I investigated each stakeholder group's relative power (i.e., political influence in decision-making), estimated their interest (i.e., level of concern, involvement, advocacy, and commitment), and identified whether they desired more, less, or the same number of local deer. For example, 1 survey question involved asking municipal representatives whether their communities generally desired more, less, or the same number of local deer. Importantly, these categories represented average values and approximations of one snapshot within a complex web of diverse stakeholders. Through this methodology, I aimed to better understand how diverse stakeholder interests influence the feasibility of sharpshooting in New England. Furthermore, this analysis informed the model interpretations (Messmer et al. 1997, Chase et al. 2000, Raik et al. 2005, NYSDEC 2018) and influenced my resulting management recommendations (West and Parkhurst 1973, Stollkleemann and Welp 2006).

3.4. Results

3.4.1. Research Question 1 (Ecological)—The line graphs reveal a negative correlation between sharpshooter access (representative of sharpshooter density) and WTD density (Figure 18). This indicates that sharpshooter and deer densities are directly related, and higher levels of sharpshooters results in lower WTD populations.

3.4.2. Research Question 2 (Theory)—The box plots reveal the positive correlation between sharpshooter access, hunting access, and hunter density (Figure 19). Average estimates demonstrate that MA requires less sharpshooting access than NY for every hunter density/access category (Figure 20), and variability in estimates generally increases as hunter density/access decreases (Table 13). The results for each town are displayed in Table 14 and described in detail below. I considered all results under 5% as indicating that 0% sharpshooting access is required.

<u>Carlisle, MA:</u> The model results suggest that Carlisle does not need sharpshooting and can maintain their local WTD population with current and 25% reduction estimates of hunter density and hunting access. Given a 50% reduction in hunter density and hunter access levels, however, then 8.2% of the town may need to be made available to sharpshooting to have the same WTD population effect. Carlisle does not currently implement sharpshooting.

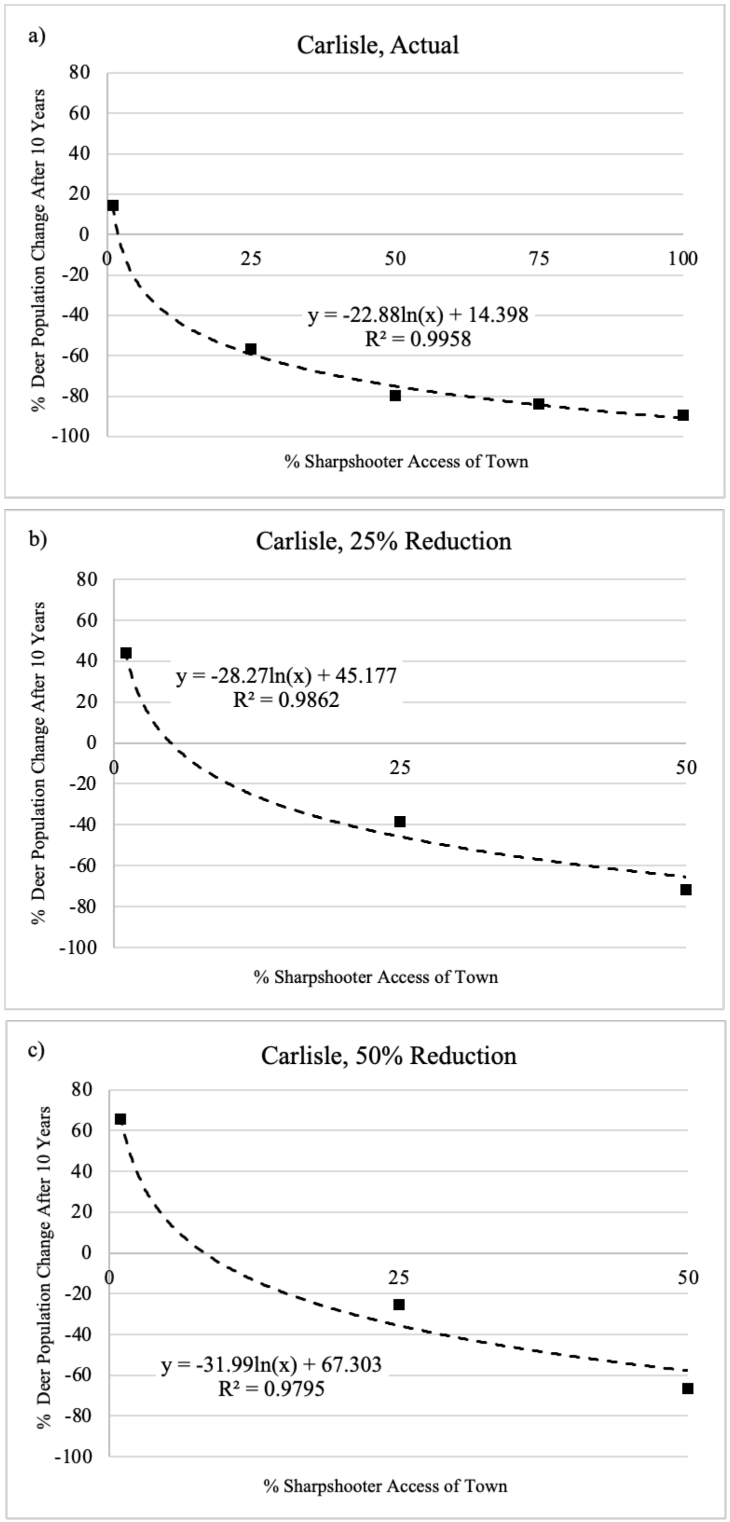


Figure 18. Carlisle model results, showing the amount of sharpshooter land access required to maintain the local WTD population under a) current (0%), b) 25% reduced (15.5%), and c) 50% reduced (21.7%) estimates of hunter density and hunting land access.

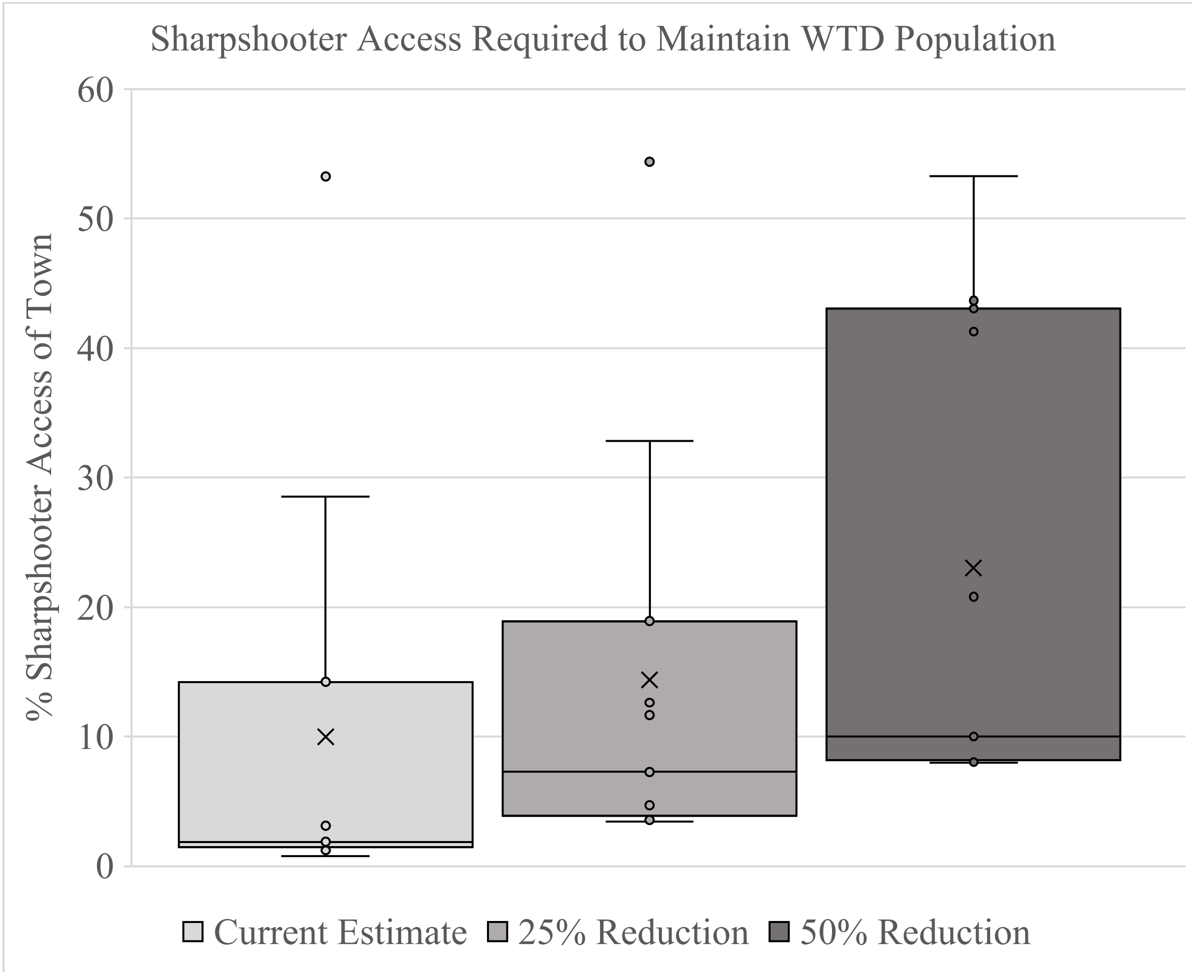


Figure 19. The estimated % sharpshooter access of the town required to maintain the local WTD population under 3 distinct scenarios. The first plot represents the level of sharpshooter access required under current estimated conditions (current hunter density and access), where the second and third plots represent the % sharpshooter land access required if there was a 25% and 50% reduction in both hunter density and land access, respectively. Outliers represent the town of Geddes, NY.

Easton, MA: The model results indicate that the town of Easton can maintain their local WTD population effectively with the existing and 25% reduced hunter density and hunting access estimates without the need for sharpshooting. If both hunter density and hunting access are reduced by 50%, the model suggests 8.4% sharpshooting access to maintain the local deer population. Easton does not currently implement sharpshooting.

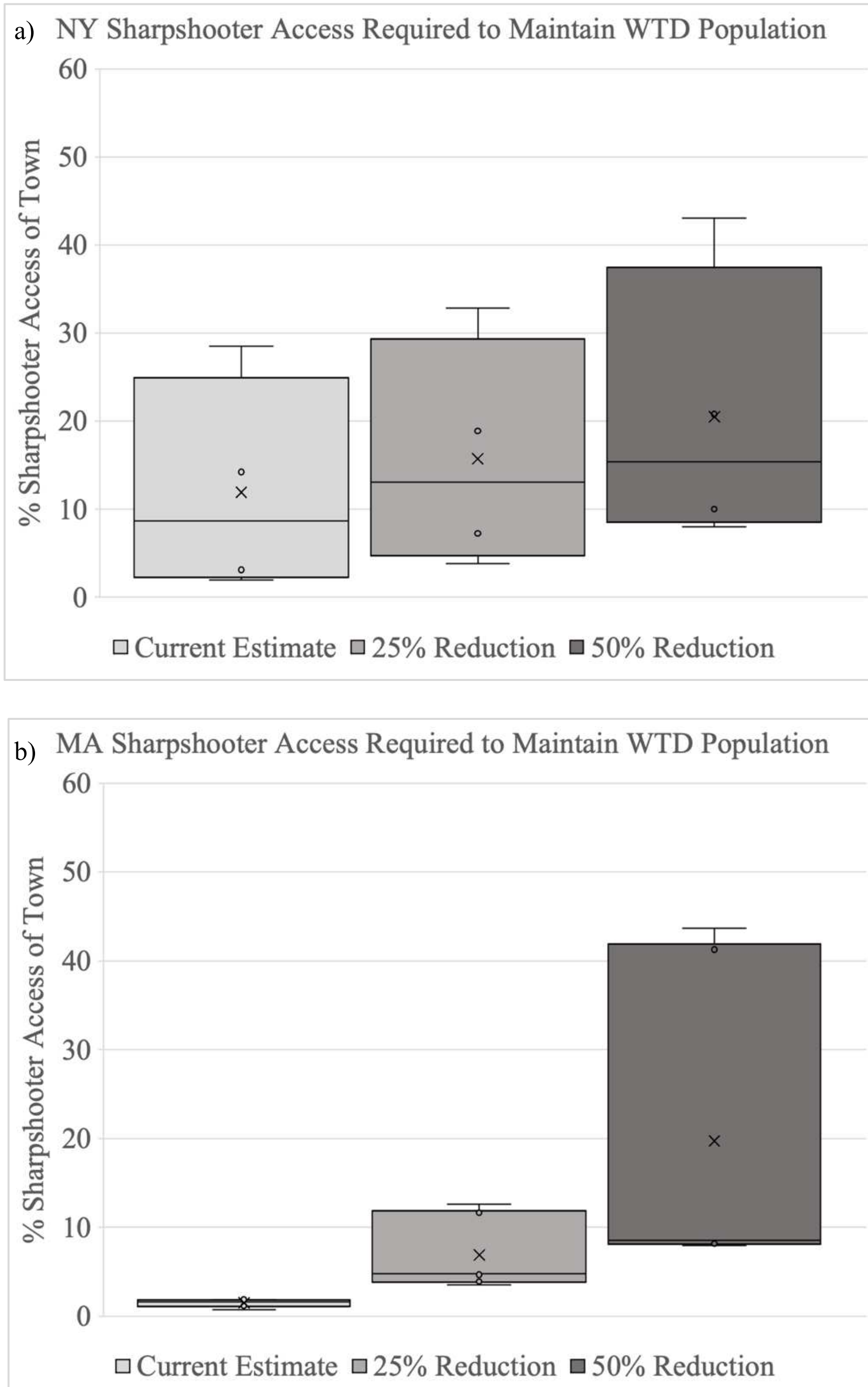


Figure 20. The estimated % sharpshooter access of the town required to maintain the local WTD population under 3 distinct scenarios in a) NY compared to b) MA. The first plot represents the level of sharpshooter access required under current estimated conditions (current hunter density and access), where the second and third plots represent the % sharpshooter land access required if there was a 25% and 50% reduction in both hunter density and land access, respectively. I removed the extreme outlier town of Geddes, NY.

Table 13. Average sharpshooting access for all towns collectively and broken into state categories (average ± SD), represented as the % of town land access required for sharpshooters such that the town effectively maintains its local WTD population (0% growth). The first column represents the currently estimated hunter density and hunting access estimates, where the second and third columns represent scenarios in which both hunter density and access decline by 25% and 50%, respectively. A negative value below 0 essentially indicates that 0% of the town is required for sharpshooter access to regulate local WTD populations.

Category	*% Sharpshooting Access for Current Hunter & Hunting Access Estimates*	*% Sharpshooting Access for 25% Hunter & Hunting Access Reductions*	*% Sharpshooting Access for 50% Hunter & Hunting Access Reductions*
All Towns	10.0 ± 16.7	14.4 ± 15.9	23.0 ± 18.3
MA Towns	1.5 ± 0.4	6.9 ± 4.1	19.7 ± 17.6
NY Towns	12.0 ± 12.3	15.7 ± 13.1	20.5 ± 16.1

Lincoln, MA: The model findings show that in Lincoln, the town effectively maintains its local WTD population under the existing and 25% reduction estimates for hunter density and hunting access, rendering sharpshooting unnecessary. In the event of a 50% reduction in both hunter density and hunting access, the model suggests that around 8.0% sharpshooting access would be required to maintain the local deer population. Lincoln does not currently implement sharpshooting.

Pepperell, MA: In Pepperell, the model's findings indicate that the town can maintain its local WTD population with existing estimates for hunter density and access, eliminating the need for sharpshooting. In the scenario of a 25% and 50% reduction in both hunter density and hunting access, the model suggests approximately 12.6% and 41.3% sharpshooting access to maintain the local deer population, respectively. Pepperell does not currently implement sharpshooting.

Sharon, MA: The model demonstrates that Sharon can effectively maintain its local deer population based on the current estimates for hunter density and access, thus rendering

Table 14. Sharpshooting access for each town, represented as the % of town land access required for sharpshooters such that the town effectively maintains its local WTD population (0% growth). The first column represents the currently estimated hunter density and hunting access estimates, where the second and third columns represent scenarios in which both hunter density and access decline by 25% and 50%, respectively. I considered all results under 5% as indicating that 0% sharpshooter access is required.

Town	*% Sharpshooting Access for Current Hunter & Hunting Access Estimates*	*% Sharpshooting Access for 25% Hunter & Hunting Access Reductions*	*% Sharpshooting Access for 50% Hunter & Hunting Access Reductions*
Carlisle, MA	1.9	4.9	8.2
Easton, MA	1.8	3.4	8.4
Lincoln, MA	1.5	4.7	8.0
Pepperell, MA	0.8	12.6	41.3
Sharon, MA	1.8	11.7	43.7
Weston, MA	1.2	3.6	8.5
Clay, NY	3.1	7.3	10.0
DeWitt, NY	53.2	54.4	53.3
Fenner, NY	2.0	3.9	8.0
Geddes, NY	14.2	18.9	20.8
Manlius, NY	28.5	32.8	43.0

sharpshooting unnecessary. If the hunter density and access levels decline by 25% and 50%, the model suggests an allocation of approximately 11.7% and 43.7% for sharpshooting access to regulate the local deer population, respectively. Sharon does not currently implement sharpshooting.

Weston, MA: The model's outcomes indicate that Weston can sustain its local WTD population effectively under paradigms of current and 25% reduced hunter density and hunting access without the need for sharpshooting. If both hunter density and hunting access decrease by 50%, the model suggests 8.5% of town land be made available for sharpshooting to promote effective management of the local deer population. Weston does not currently implement sharpshooting.

Clay, NY: For Clay, the model suggests that the town can effectively manage local WTD populations without the need for sharpshooting based on current estimates of hunter density and hunting access. With a 25% and 50% reduction in hunter density and hunting access, however, the model indicates that 7.3% and 10.0% of town lands would need to be open for sharpshooting to have the same deer population effect, respectively. Clay does not currently implement sharpshooting.

DeWitt, NY: According to the model findings, in DeWitt, approximately 53.2% of the town should be available for sharpshooting to efficiently maintain the local WTD population, assuming the current estimates for hunter density and access. Notably, hunting is not allowed in DeWitt so the estimates for 25% and 50% reductions of hunter density and hunting access are similar to the current estimate and only fluctuate due to inherent variability in simulation outcomes. Currently, around 50% of town lands in DeWitt are open for sharpshooting.

Fenner, NY: Based on the model's results, Fenner can effectively maintain their local WTD population without the implementation of sharpshooting, assuming the current and 25% reduced hunter density and access estimates. With a 50% decline in hunter density and hunting access, the model suggests 8.0% of the town's area should be open to sharpshooting to manage the local deer population. Fenner does not currently implement sharpshooting.

Geddes, NY: According to the model's findings for Geddes, the town requires between 14.2% and 20.8% open sharpshooting access to maintain local WTD populations. There is no hunting allowed in Geddes, so variation in results is a byproduct of inherent model variability and all outcomes reflect situations with no hunting in the town. Geddes currently has approximately13% of town lands available for sharpshooting.

Manlius, NY: In Manlius, the model suggests that approximately 28.5%, 32.8%, and 43.0% sharpshooter access is required to maintain local deer herds under scenarios of current, 25% reduced, and 50% reduced hunter density and hunting access estimates. Manlius currently has approximately 24% of town lands open for sharpshooting.

The model results demonstrate that, based on current estimates, most towns (except DeWitt, Geddes, Manlius, and marginally, Clay) can effectively maintain their local deer populations without sharpshooting. However, with a 25% reduction in hunter recruitment and land access, the results suggest that between 3.4% (essentially 0%) and 54.4% of town lands should be made available to sharpshooters to have the same deer management effect. Similarly, with a 50% decline in hunter density and hunting access, the models imply that sharpshooting access would need to be between 8.0% and 53.3% of town lands to stabilize local deer populations.

The sensitivity analysis for the town of Manlius reveal that changes in hunting land access (Figure 21*a*), hunter population (Figure 21*b*), and initial deer population (Figure 21*c*) substantially affect results (Table 15). Changing hunting access to 0% of the town yields the greatest deviation from the current estimate, resulting in a 65.3% ($t(29) = 32.2892$, $p < 0.001$, two-tailed) change. This suggests that, in this context, sharpshooting becomes ineffective without hunters given the current sharpshooting access level. Having 50% to 100% open hunting access also significantly changes the results from 16.4% ($t(29) = -6.0527$, $p < 0.001$, two-tailed) to 23.0% ($t(29) =-8.4717$, $p < 0.001$, two-tailed), though there is a point of diminishing returns at

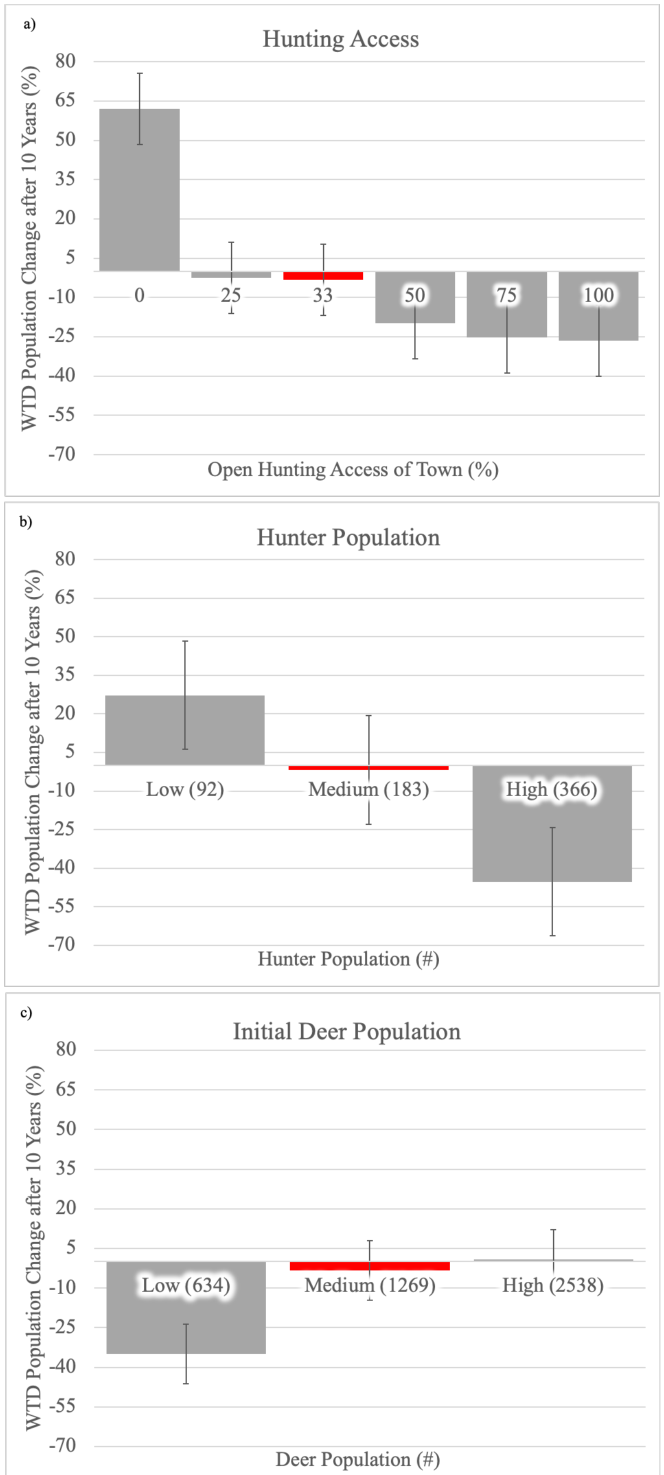


Figure 21. Sensitivity analysis results depicting how changes in a) hunting access up to 65.3% change), b) hunter population (high: 43.4% change; low: 29.0% change), and c) initial deer population (high: 4.2% change; low: 31.5% change) impacted outcomes. Gray bars indicate directional change from the current estimates (represented by the red bars) with standard error bars.

Table 15. One-at-a-time factorial sensitivity analysis results depicting the percent (%) that the outputs fluctuated from the current estimate when a single parameter value was changed.

Variable Changed	*Percent (%) Change of Result from Current Estimate*
Low Hunter Population (93)	29.0*
Medium Hunter Population (*Current Estimate*, 183)	0.0
High Hunter Population (366)	-43.4*
0% Hunting Access	65.3*
25% Hunting Access	0.9
33% Hunting Access (*Current Estimate*)	0.0
50% Hunting Access	-16.4*
75% Hunting Access	-22.0*
100% Hunting Access	-23.0*
Low Initial Deer Population (634)	-31.5*
Medium Initial Deer Population (*Current Estimate*, 1269)	0.0
High Initial Deer Population (2538)	4.2

* Statistical significance

around 50% access. Having 25% access does not significantly change outcomes from the current estimate of 33% ($t(29) = 0.8098$, $p = 0.4267$, two-tailed). Initializing the model with a low and high hunter population result in statistically significant outcomes deviating 29.0% ($t(29) = -30.687$, $p < 0.001$, two-tailed) and 43.4% ($t(29) = 19.105$, $p < 0.001$, two-tailed) from the current estimate, exemplifying the critical role of hunters in determining sharpshooting intensity. Starting with half or twice as many deer also influence outcomes, resulting in statistically significant 31.5% ($t(29) = -18.102$, $p < 0.001$, two-tailed) and insignificant 4.2% ($t(29) = 1.2625$, $p = 0.2168$, two-tailed) deviations from the expected values, respectively. This result suggests that municipalities can more readily manipulate low deer populations, and municipalities may have equally effective management effects with high deer densities. Based on the absolute values of the percent changes, the parameter changes collectively impact results on average by 26.2% (maximum: 65.3%, minimum: 0.9%).

3.4.3. Research Question 3 (Social)—Stakeholder groups participating in the management of New England WTD populations encompass a wide range of entities, including: the general public; various agencies (both private and governmental) related to wildlife, land, safety, health, and agriculture; interest groups focused on animal rights, environmental conservation, and professional societies; as well as foreign nations, poachers, and various other organizations. Key players include the public, hunters, sharpshooting organizations, and state wildlife agencies. This multifaceted group of stakeholders is characterized by intricate relationships and interactions shaped by behaviors, intentions, interrelations, agendas, interests, and influences within each group (Brugha 2000).

Management decisions are often shaped by varying perceptions and experiences among these stakeholders, leading to a wide spectrum of viewpoints (Stollkleemann and Welp 2006, Smith 2009). A key distinction among these perspectives lies in their general inclination towards desiring more, less, or the same number of WTD in the region. While many groups advocate for fewer WTD, motivated by factors like financial considerations (e.g., car insurance costs) (Conover et al. 1995, Knoche and Lupi 2007, Duda et al. 2021), public health concerns (e.g., Lyme disease) (Langenberg et al. 2009, Samuel et al. 2009, Belsare et al. 2020, Clark and Bidaisee 2021), or scientific findings (e.g., MassWildlife), there are also vocal groups pushing for more WTD, often including hunters, wildlife user groups (e.g., photographers), and food pantry organizations (DeNicola et al. 2000, Vercauteren et al. 2011). Some groups, such as animal rights organizations, prefer to maintain the current population levels due to non-interference principles, while conservation groups may aim for a lower, stable population.

The dynamics within these groups are influenced by power structures and authority, with each group having varying levels of influence in decision-making processes (Brugha 2000, Raik et al. 2008, Nugent et al. 2011, Levin et al. 2012, Droe 2021). The interactions range from situations where the public provides input at conservation council meetings to instances where broad power-sharing rules dictate interactions, such as when citizens vote equally (Decker and Chase 1997). In some cases, management decisions are solely driven by scientific findings, while in others, stakeholder opinions significantly sway the outcomes (Pérez-Espona et al. 2009, Meek 2013, Feng et al. 2021). Both NY and MA have established processes aimed at accommodating the diverse desires of stakeholders, including public meetings, surveys to capture broad ranges of opinions, and open invitations for community input through various channels. After I conducted interviews with local representatives, it became evident that officials are deeply committed to accurately representing community interests while carefully considering the consequences of each decision.

For the stakeholder analysis, I identified 26 of the most relevant stakeholder groups and plotted their interest level against their level of power (Figure 22). This decision rationale was based on my intuition regarding an approximation of the current New England deer management system after speaking with state wildlife agencies, interviewing municipal representatives, consulting with experts, and reviewing the literature. Most stakeholders fall in the category of low interest-low power, or high interest-high/medium power (Table 16). Notably, I did not

Stakeholder Interest-Power Grid

Power (Political Influence)	LOW	MEDIUM	HIGH
HIGH		• Professional Conservation Societies	• General Public • Legal and Regulatory Bodies • Animal Rights Activist Groups • State Wildlife Agencies • Tourism and Recreation Businesses • Wildlife Resource User Groups
MEDIUM	• Poachers	• Federal Wildlife Management Agencies • Public Land Agencies • Educational Institutions	• Agricultural Agencies • Environmental Groups • Indigenous Communities • Local Governments • Neighboring Communities • Private Wildlife Agencies
LOW	• Emergency Responders • Hospitals • Insurance Companies • Foreign Nations • Other Groups • Media and News Outlets	• Transportation Agencies • Wildlife Rehabilitation Centers • Non-Profit Motivated Private Landowners	

Interest (Commitment, Dedication, Advocacy, etc.)

Figure 22. Stakeholder Interest-Power Grid depicting the 26 most relevant identified stakeholder groups distributed according to their level of interest (x-axis) and power (y-axis).

Table 16. The stakeholder interest-power heatmap of the interest-power grid, showing that the majority of stakeholder groups fell under the low power, low interest category or the high/medium power, high interest category.

	Interest		
Power	Low	Medium	High
Low	0	1	6
Medium	1	3	6
High	6	3	0

discover any stakeholder groups occupying the other extreme ends of the power-interest spectrum (high power-low interest and high interest-low power). Of the groups that fall under medium or high interest and medium or high power (*n* = 16), I determined that 3 generally desire more local deer, 6 are neutral or prefer the same number of deer, and 7 want less based on surveys, interviews, expert opinion, and the literature (Table 17). Notably, these are average approximations of each group and only represent broad generalizations as there is variability within each group.

Table 17. Stakeholder deer preferences of the stakeholder groups that desire more (*n* = 3), the same amount (*n* = 6), or less (*n* = 7) local WTD from groups identified in the medium or high interest and medium or high power categories.

Desire for More Local WTD	Neutral or Desire for Same Number of Local WTD	Desire for Less Local WTD
• Private Wildlife Agencies • Tourism and Recreation Businesses • Wildlife Resource User Groups	• Education Institutions • Indigenous Communities • Local Governments and Municipalities • Neighboring Communities • Animal Rights Activist Groups • State Wildlife Agencies	• Federal Wildlife Management Agencies • Public Land Agencies • Agricultural Agencies • Environmental Groups • Professional Wildlife Management and Conservation Societies • General Public • Legal and Regulatory Bodies

3.5. Discussion

In this study, I aimed to assess the relationships between sharpshooter and hunter density and access, social attitudes regarding sharpshooting, and WTD density in New England. I sought to explore the ecological, theoretical, and social dimensions of this system, ultimately aiming to investigate the feasibility of sharpshooting in controlling New England WTD populations.

3.5.1. Research Question 1 (Ecological)—The results demonstrate the negative correlation between sharpshooter and WTD density (Figure 18); as sharpshooter density increases, WTD density declines. Remembering that the models show consistent sharpshooter densities within access areas, their increased town density is implied as their access increases. Collectively, the results suggest that most towns can currently maintain their local WTD populations without the need for sharpshooting. Furthermore, the model implies that towns will continue to successfully manage local deer with current implementations even if the deer population doubles (Figure 21). However, the sensitivity analysis suggests that if a municipality can reduce its local WTD population to half the amount, they may have an easier time controlling the population with less intensive efforts (Figure 21). Though previous studies have questioned whether sharpshooting has localized or regional impacts on WTD densities, these results indicate that this method can have broader population impacts when sharpshooting access is great enough. These results support my ecological hypothesis that (H_1) sharpshooter density is negatively correlated with WTD density due to an increased culling presence.

3.5.2. Research Question 2 (Theory)—The outcomes reveal the positive correlation between sharpshooter access and hunting access/density (Figure 20), showing that the requirement of sharpshooting access to maintain local deer herds increases as hunter recruitment and hunting land access decline (Figure 19). The sensitivity analysis findings emphasize the importance of considering hunting access and hunter density when considering the efficacy and feasibility of sharpshooting programs (Figure 21). A town with a reduced hunter population (half the size) may face considerable challenges in maintaining the local deer population, even when sharpshooting is implemented. Conversely, a town with a hunter population twice as large may find sharpshooting unnecessary for effective population control. Similarly, the level of hunter access can influence the efficacy of sharpshooting, though hunters may reach a point of diminishing returns when paired with sharpshooting (Figure 21). Other studies have reported the greater efficacy of sharpshooting when combined with hunting compared to other management methods (DeNicola and Williams 2008, Williams 2008, Williams et al. 2013, Figura 2017). These outcomes support my theoretical hypothesis that (H_2) sharpshooter access is positively correlated with hunter density and hunting access due to a trade off in harvest effects.

3.5.3. Research Question 3 (Social)—The stakeholder analysis results demonstrate the positive correlation between stakeholder acceptance of sharpshooting and its efficacy (

Figure 22). Depending on the context and makeup of community preferences, communities can either support, reject, or be neutral towards the implementation of sharpshooting programs (Table 16). The variation in stakeholder values and preferences across municipalities can pose challenges within these systems, as exemplified by other studies in the literature (West and Parkhurst 1973, Stollkleemann and Welp 2006, Davies and White 2012). These findings highlight the important role of stakeholder engagement and acceptance in fostering collaborative approaches, especially in cases where stakeholders have opposing views (Stout and Knuth 1995, Messmer et al. 1997, Raik et al. 2005, Leong et al. 2009).

The absence of any stakeholder groups falling into the high power-low interest or high interest-low power categories underscores the divergent nature of this subject and the ability of stakeholder groups to leverage influence to meet their goals (Table 16) (Leong et al. 2009, Davies and White 2012). For example, if a stakeholder group holds significant power over WTD sharpshooting decision-making, the results suggest they would actively engage with and take interest in the topic. Conversely, stakeholder groups with high interest and no power are likely to seek sources of power to leverage for their cause. Notably, some stakeholders, while not constituting the majority (e.g., animal rights activist groups,

Figure 22), can hold considerable influence on management outcomes due to their persistent advocacy against sharpshooting (Micklin 1984, Leong et al. 200). This illustrates the dynamic capacity of stakeholder groups, especially those with high interest and power, to instigate systematic change even when they do not proportionally represent the broader community (Smith 200). These results support my social hypothesis that (H_3) community acceptance of sharpshooting is positively correlated with the efficacy of this strategy due to enabling factors such as increased access for management implementation.

3.5.4. Management Recommendations—Based on the results, I crafted social and ecological WTD management recommendations regarding sharpshooting for towns in New England:

1. Population Assessment and Data-Driven Decisions:
   a) Base sharpshooting decisions on a thorough evaluation of scientific data, stakeholder acceptance, and ecological considerations.
   b) Continuously monitor social and ecological outcomes of sharpshooting programs and adjust management as needed.
2. Stakeholder Engagement and Community Collaboration:
   a) Involve stakeholders throughout all phases of the decision-making processes.
   b) Seek public input through surveys and town hall meetings to gauge community preferences and build support.
   c) Collaborate with neighboring communities and organizations to coordinate WTD management efforts, share best practices, and address regional population dynamics.

d) Explore and consider non-lethal alternatives, especially in areas where lethal control methods face resistance.

3. Professional Sharpshooters and Effective Protocols:

   a) Hire experienced and well-qualified sharpshooting teams or wildlife management agencies to carry out operations.

   b) Implement strict safety protocols, such as setting up safety zones, using noise-reducing equipment, and conducting operations at night.

   c) Focus on achieving high accuracy and efficiency to minimize animal suffering, maximize effectiveness, and increase stakeholder support.

   d) Utilize harvested WTD carcasses whenever possible by donating them to food banks or wildlife rehabilitation centers.

Additionally, I suggest that our focal communities invest in solutions that amplify hunter recruitment and secure land access if they wish to continue relying on hunting for local WTD management. As long as the current approaches remain effective in achieving both social and ecological goals, the consideration of sharpshooting may be unnecessary. Therefore, the decision to adopt sharpshooting should be seen as a contingent measure, with a strong emphasis on community involvement and support to promote the continued success of deer management efforts, as emphasized in previous research (Stout and Knuth 1995, Raik et al. 2005, NYSDEC 2018).

3.5.5. Limitations—In context of the stakeholder analysis, an important limitation pertains to the dynamic nature of interest and power dynamics, which are in constant flux within the realm of sharpshooting in New England. The findings provide a single snapshot of a constantly fluctuating system, making it essential to acknowledge that stakeholder dynamics can be radically different between towns and within towns at different times or in other contexts. Furthermore, this study focused on the broader New England WTD management system and trends across focal towns, but certain aspects may be more relevant to some places than others. For instance, the involvement of Indigenous Peoples in the sharpshooting discourse is limited to a select few towns, and certain stakeholder group influences are indirect, such as federal government involvement. This limitation underscores the need to recognize that these results capture a momentary perspective within the context of addressing overabundant WTD concerns through sharpshooting in New England.

There are also inherent limitations when it comes to understanding the models. When interpreting results, it is important to note that the emphasis should be on understanding trends rather than absolute numerical values (Wilensky and Rand 2015). These models should not be interpreted as providing definitive truths but rather as a starting point for meaningful discussions and analyses (Railsback and Grimm 2019). For example, if the outcome suggests that 25% of town land should be available for sharpshooting to achieve effective local WTD management, this is not a precise fact but rather a topic for discussion. These results should be regarded as tools to stimulate dialogue and critical thinking, prompting consideration of why these specific trends were generated and what real-world implications they may hold (Resnick 1994). The outcomes do not offer a one-size-fits-all solution, but they provide a foundation for exploring the complexities of WTD sharpshooting in New England, accounting for various ecological, theoretical, and social factors (Sterman 2001, Bonabeau 2002, Railsback and Grimm 2019).

Another important consideration revolves around the reliance on parameter estimates in these models, which are approximations rather than precise values. I programmed the models to exhibit stable WTD populations under current conditions based on averages of a 20-year town-specific dataset demonstrating population stability. This assumption likely shaped the model results, and any variation in the data could have yielded different outcomes. Ultimately, these models should be viewed as simplifications or abstractions of complex systems (Wilensky and Rand 2015), and their parameter estimates can be fine-tuned with more monitoring data.

These models are not standalone assessments, and I purposefully did not design them to capture all aspects of the real system due to the need for simplicity, understandability, and model functioning constraints (Wilensky and Shargel 2002, DeAngelis and Grimm 2014, Wilensky and Rand 2015). For example, they represent closed systems that do not account for the complex sharpshooter and WTD dynamics in the real world. They also assume uniform behavior for all agent types, simplifying the real system and potentially introducing biases (Grimm et al. 2020). In reality deer will immigrate and emigrate across regions, and individuals have unique behaviors (Riley et al. 2003, Williams et al. 2008). While these simplifications are necessary in this context to assess underlying system dynamics and address the research questions, they should be recognized as limitations.

Recognizing the limitations of this project allowed for the implementation of mitigation techniques that enhanced reliability of results. To mitigate project limitations, I defined model success criteria *a priori*, leveraged a mixed-methods strategy (Strijker et al. 2020), and employed pattern-oriented modeling techniques to validate the models against observed patterns (Wilensky and Rand 2015, Railsback and Grimm 2019). I also carefully considered data sources, selecting those with rigorous study designs that represented recently collected data as close to the study area as possible (NYSDEC 2007, 2021, MassWildlife 2020). Furthermore, I crafted the models to specifically address the research questions with a central focus on representing key phenomena of interest (Railsback and Grimm 2019, Grimm et al. 2020).

3.5.6. Significance and Implications—This research enhances our understanding of urban WTD sharpshooting in New England, addressing knowledge gaps and supporting science-based WTD management approaches (Raik et al. 2005). New England's urban landscapes, coupled with evolving ecological and social dynamics, present distinct challenges for managing rising WTD populations in urban settings (O'Shea 2009). The findings offer insights for urban wildlife decision-makers, state wildlife agencies, policymakers, and the public in the region. By exploring the potential impact of sharpshooting programs, this research provides a roadmap for adaptive strategies to meet the changing needs of local urban WTD populations and coexisting communities (Goertz 2006, Baggio 2011, McArthur and Baron 1983). These insights encourage a proactive approach to ecological balance and social concerns, contributing to the long-term well-being of urban communities and resident WTD populations in New England.

The practical implications of this research primarily revolve around providing tailored recommendations for urban WTD management. These recommendations are informed by empirical data and analysis, offering actionable strategies for balancing WTD population management with urban ecological and social goals (Riley et al. 2003, O'Shea 2009, Tack et al. 2018). They enable urban stakeholders to make informed decisions that align with urban social and ecological objectives (Droe 2021, McArthur and Baron 1983). Emphasizing the importance of stakeholder acceptance, this study underscores the need to consider social dimensions in urban wildlife management (Levin et al. 2012, Lindenmayer et al. 2012, Baggio 2011).

Beyond its regional relevance, this research highlights the broader importance of applying scientific rigor to evaluate urban WTD management systems. Managing wildlife in urban settings is a complex endeavor influenced by multifaceted factors, and agent-based model analysis of these systems can contribute to the development of systematic, evidence-based approaches to urban wildlife management (Van Buskirk et al. 2021, Xie et al. 1999). The versatility of this modeling framework extends beyond urban WTD management and is applicable to addressing deer challenges in other settings across a gradient of urban to rural environments. Furthermore, applying this modeling approach to other contexts can also offer insights into managing conflicts involving different species in diverse geographic locations (Tang and Bennett 2010).

3.5.7. Suggestions for Future Research—Future research regarding the efficacy of sharpshooting as an urban WTD management strategy in New England presents exciting opportunities to build upon the insights gained from this study. First and foremost, exploring the long-term impact of sharpshooting on WTD populations and related social and ecological systems may provide valuable insights (Callahan 1984, Franklin 1989, Lindenmayer et al. 2012). Tracking the outcomes over extended periods can help to inform the sustainability and effectiveness of sharpshooting across different contexts (DelGiudice et al. 2010, Figura 2017*a*, Dinca et al. 2018). Similarly, comparative studies across different regions can offer further insights into the effectiveness of sharpshooting in various ecological and social contexts (West and Parkhurst 1973, Siemer et al. 2004, Stollkleemann and Welp 2006, Davies and White 2012). These studies can identify best practices and factors that apply to different locations, helping to inform more tailored WTD sharpshooting program development.

Continuously improving modeling techniques such as those used in this study is also an important area for future research (Railsback and Grimm 2019). This may include enhancing parameter estimates, exploring real-world migration and emigration data, and refining sensitivity analyses to pinpoint critical factors influencing sharpshooting outcomes (Wilensky and Rand 2015, Strijker et al. 2020). Investing in the ecological component of this project, research into the advancements of tracking and monitoring technology to better understand WTD movement patterns, population dynamics, and habitat preferences can contribute to more precise and informed urban management decisions (Chrétien et al. 2016). Expanding research to explore the broader ecological impact of sharpshooting methods is also important (Franklin 1989). Assessing how sharpshooting directly and indirectly influences the entire ecosystem, including plant communities and other wildlife species, is essential for holistic sharpshooting implementation (Garrott et al. 1993, Côté et al. 2004, Klein 2012).

Because each community can be vastly different from their neighbor when it comes to experiences and beliefs about sharpshooting (McArthur and Baron 1983, Leong et al. 2009, Smith 2009, Davies and White 2012), understanding community engagement and perceptions is another possible area for future investigation (Stout and Knuth 1995, Raik et al. 2005, NYSDEC 2018). Research that delves into community attitudes and preferences about sharpshooting can help tailor strategies to gain wider acceptance and support, ultimately leading to more successful and effective sharpshooting programs (West and Parkhurst 1973, Messmer et al. 1997, Chase et al. 2000, Stollkleemann and Welp 2006, Davies and White 2012). In addition, researchers could explore the regulatory frameworks and governance structures surrounding sharpshooting by evaluating the effectiveness of policy interventions and their alignment with ecological and social objectives (Nugent et al. 2011, Levin et al. 2012, Feng et al. 2021). Investigating the broader spectrum of this urban human-wildlife conflict—including economic and safety aspects—can help inform more inclusive sharpshooting programs that address the multifaceted challenges associated with growing urban WTD populations (McArthur and Baron 1983, Knoche and Lupi 2007, 2012, Wagner et al. 2010, Levin et al. 2012, Droe 2021).

3.6. Conclusion

This study embarked on an investigation into the complex world of WTD management in New England, with an emphasis on the strategy of sharpshooting for population control. It provided historical context for WTD management in North America and highlighted the need for innovative approaches to address constantly shifting ecological and social dynamics. In this research, the primary aim was to address critical questions surrounding the efficacy of sharpshooting as a management strategy for controlling WTD populations in New England. The project sought to determine the extent to which sharpshooting may be necessary, the conditions under which it could be effective, and the role of stakeholder acceptance in shaping its success. Through this multidimensional analysis, the overarching study goal was to contribute insights to the ongoing discourse regarding potential WTD sharpshooting programs in New England.

The literature review provided a complete overview of sharpshooting as a WTD management strategy, alluding to its ecological, social, and theoretical dimensions through history. Through this review, it became evident that the consideration of sharpshooting as a WTD management strategy in New England was a complex challenge with multifaceted ecological and social implications. As overabundant WTD populations can lead to issues like increased vehicle collisions, plant and agriculture damage, and heightened disease prevalence, the need for effective urban management strategies is ever pressing. Sharpshooting, despite its controversial nature, represents a viable and humane alternative in situations where hunting methods fall short, particularly in urban areas where safety concerns and regulations often prohibit conventional hunting. This review underscores that the success of sharpshooting hinged on several key factors, including stakeholder acceptance and involvement, precision of sharpshooter execution, and transparency in stakeholder communication.

In a rapidly changing landscape characterized by a declining hunter population and limited land access, sharpshooting may offer a pragmatic solution to the challenges posed by WTD overabundance. Its adaptability to different environments, precision in culling targeted individuals, and ability to address safety concerns in urban areas makes it a plausible tool for modern WTD management in urban environments. The efficacy of sharpshooting can hinge on proper public education, policy adjustments, technological advancements, and stakeholder collaboration. Incorporating these approaches can help increase support, improve data accuracy, and promote ethical standards, ultimately leading to more successful outcomes. Like any management method, sharpshooting has potential pitfalls, and its success is highly context dependent. Inadequate training, improper execution, and lack of stakeholder support could lead to failures or unintended animal suffering, illustrating how balancing conflicting interests remains a top priority when it comes to sharpshooting efficacy.

Based on the goal of addressing knowledge gaps and assessing efficacy of WTD sharpshooting programs in New England, I created agent-based models that focused on relevant scenarios. The strategic selection of representative towns in NY and MA enabled a novel and comparative landscape to robustly address the research questions. With a mixed methods research approach and a repeated cross-sectional time horizon, the project used qualitative and quantitative survey data combined with computer simulation modeling to address research questions. By combining both social and ecological data, I aimed to establish a solid foundation of scientific evidence to assess the underlying mechanisms guiding the WTD sharpshooting management system. This dataset aimed to provide a deeper understanding of the complex natural-human system of WTD management in New England across space and time. I conducted

1,650 simulation runs to address the research question, and 6,750 runs for a sensitivity analysis to assess how results changed in response to variation in input parameters.

The results of this study provided insights into the efficacy of sharpshooting as a WTD management strategy in New England. The findings for each focal town revealed that the need for sharpshooting varies based on factors such as current hunter density and access estimates. While some towns (e.g., Carlisle) could effectively maintain their local WTD populations without sharpshooting, others (e.g., Pepperell) may benefit from its implementation under certain conditions. However, with a declining hunter population and anticipated less hunting access, all towns may need to increase sharpshooting access to have the same deer population effects. The sensitivity analysis highlighted the inherent variability of input variables, emphasizing the need for further monitoring and evaluation to inform decision-making. These findings may be important for wildlife decision-makers when it comes to understanding the scale of operations needed when considering sharpshooting as a future management strategy. It is crucial to note that sharpshooting's efficacy not only depends on its technical feasibility, but it also critically hinges on its acceptance by stakeholders.

These results underscore the importance of tailoring management strategies to the specific needs and contexts of each community. The stakeholder analysis revealed the complex web of relationships and motivations among diverse stakeholder groups regarding WTD sharpshooting, ranging from sharpshooters and hunters to the general public and animal rights activists. Recognizing areas of common interest and involving stakeholders throughout the decision-making processes is crucial for implementing successful sharpshooting programs. Based on the findings, I provided specific management recommendations to towns in New England regarding implementation of WTD sharpshooting. By adhering to these management recommendations and adopting holistic, tailored, and adaptive approaches, communities can increase their chances of success when considering WTD sharpshooting programs in New England. This study highlighted the importance of considering not only ecological aspects but also social dimensions, particularly the role of community acceptance in shaping sharpshooting success.

While most towns can currently manage their WTD populations without sharpshooting, proactive measures to enhance hunter recruitment and land access are important in sustaining the efficacy of hunting. In addition to the practical implications of extending management recommendations to focal towns, the results can also serve as a template for wildlife managers in other areas facing similar challenges. Recommendations for future research include long-term impact assessments, improving modeling techniques, exploring ecological effects, understanding community engagement, analyzing regulatory frameworks, and linking ecological and social aspects to develop inclusive management strategies. Investing in these avenues of research will advance our understanding of WTD sharpshooting and can ultimately inform more effective, sustainable, and socially acceptable approaches in this complex coupled natural-human system. By integrating agent-based modeling and considering ecological and social factors, this research has helped the discipline gain a more holistic understanding of how sharpshooting can fit into the broader landscape of WTD management.

4. THE IMPORTANCE OF MUNICIPAL COORDINATION IN NEW ENGLAND WHITE-TAILED DEER MANAGEMENT

4.1. Summary

Though once extirpated across most of the US, high populations of white-tailed deer (*Odocoileus virginianus*, henceforth WTD) have recently presented a complex management challenge across New England landscapes (Kelly 2018). WTD are known for their adaptability and prolific reproductive rates, and they have recently become a familiar presence in the urban environments of New England. Their skyrocketing populations have led to increased human-deer conflicts and ecological imbalances, highlighting the need for more extensive research and effective management solutions. However, managing their populations across fragmented landscapes and amidst diverse stakeholder interests presents many challenges.

Untangling social and ecological complexities along the way, I aim to address the importance of WTD management coordination through a theoretically-driven, abstracted agent-based model. The model simulates interactions between deer, hunters, sharpshooters, and their shared environments across spatial scales in New England. Furthermore, I analyze 4 common management approaches: recreational hunting, professional sharpshooting, the combination of hunting and sharpshooting, and no harvest (lack of management). Parameterized with social and ecological data estimates from New York and Massachusetts, the goal of this model is to provide theoretical insights into WTD management coordination of the New England region. By identifying thresholds of efficacy, this study delves into the foundational dynamics of these

intricate management systems, providing a platform to facilitate dialogue and encourage development of sustainable solutions for these coupled natural-human systems.

The results suggest that, based on current New England deer management, only the combination of sharpshooting and hunting is effectively reducing local WTD densities in the region. The outcomes also imply that increased levels of management coordination lead to reduced regional WTD densities. Notably, there is a simultaneous decrease in the deer density of towns with lethal management implemented compared to towns without management, underscoring the indirect effects that coordination may impose beyond managed areas. Moreover, the model indicates that 100% management coordination is necessary to achieve significant WTD population reductions in the region, highlighting the importance of stakeholder education and engagement, policy and cooperation, and large-scale initiatives. I also uncover a trade-off between accommodating diverse local stakeholder interests and achieving successful regional control of deer populations, an important consideration when understanding the feasibility of various management strategies in this region and others. This research adds a novel dimension to the deer management discourse by exploring the coordination of these strategies through an agent-based modeling perspective. Moreover, the findings suggest that enhanced coordination of lethal methods such as sharpshooting and resulting lower deer densities may increase the feasibility of alternative management strategies such as non-lethal fertility control. The methodology provides a blueprint not only for enhancing WTD management in New England, but also for addressing similar challenges with other wildlife species in human-dominated landscapes, ultimately contributing to a more harmonious and sustainable future.

4.2. Introduction

In the juxtaposition of two neighboring municipalities, separated only by an imaginary political boundary, a compelling narrative of white-tailed deer (*Odocoileus virginianus*, henceforth WTD) management coordination emerges. On one side, the growth of deer populations is embraced as residents desire more deer for photographing. On the other side, residents grapple with the consequences of unchecked deer growth, from garden destruction to increased road accidents. In this setting, the management disparity may lead to source-sink dynamics of deer and immense frustration and conflict between adjacent communities. This stark contrast in management strategies underscores the complex trade-off between accommodating diverse interests and achieving effective regional deer population control. This realistic New England scenario exemplifies the challenges posed by disjointed management coordination across the region, and highlights the need for a science-based exploration of the system.

The historical trajectory of WTD populations in North America serves as a foundational backdrop to understand the current state of their management coordination. Over the course of North American history, WTD populations have experienced significant fluctuations. In colonial times, when vast, undisturbed forests dominated the American landscape, WTD were moderately distributed across the continent (Kelly 2018). However, by the turn of the 20th century, their numbers sharply declined due to a combination of habitat loss and unregulated hunting practices (Heffelfinger et al. 2013). Conservationists like Aldo Leopold brought attention to the unsustainability of unregulated hunting practices (Leopold 1933), prompting the development of the North American Model of Wildlife Conservation—an instrumental historical landmark that elevated wildlife to the status of a cherished resource rather than an exploitable commodity (Dart et al. n.d., Heffelfinger et al. 2013). Successful restoration efforts, the removal of predators, and the fact that deer can reproduce very rapidly all contributed to the skyrocketing deer populations we see today.

In recent decades, the amount of human-deer conflict has surged in tandem with the expansion of both human and WTD populations (DeNicola et al. 2000), highlighting the importance of evaluating system dynamics to inform sustainable solutions. This issue is particularly pronounced in areas where residential development encroaches upon wilderness environments, known as the wildland-urban interface (Radeloff et al. 2005). Urbanization continues to expand throughout the country, often leading to habitat loss for WTD and pushing them into novel environments like urban and suburban areas, where food is abundant and there is protection from predators and hunters (DeNicola et al. 2000, Fischer et al. 2015). This expanding overlap between human and WTD environments has given rise to the field of urban ecology, which explores the consequences of these interactions (Tanner et al. 2014), as studied in this project through variable management coordination efforts.

The varied distribution of overabundant deer can pose challenges in coordinating their management across contexts. When communities refer to local deer populations as overabundant, they typically perceive the population to have crossed biological or cultural carrying capacities (Adams and LaFleur Villarreal 2020). Uncoordinated management efforts can lead to overabundant WTD populations, with detrimental effects on both natural ecosystems and human communities (Boulanger et al. 2014). These effects encompass issues such as damage to vegetation (Tremblay and Côté 2004, NDTC 2008), increased vehicle collisions (Conover et al. 1995), the spread of diseases like Lyme disease (Clark and Bidaisee 2021), crop depletion (Tremblay and Côté 2004, Nugent et al. 2011), and disruptions in nutrient cycling (Nuttle et al. 2011, NYSDEC 2018). However, other studies have acknowledged the important socioeconomic and ecological services provided by deer when their numbers are in alignment with community preferences (Hanberry 2021).

Deer interactions with communities are heterogeneous in nature, giving rise to divergent stakeholder preferences that introduce challenges in coordinating regional efforts. The debate over the optimal size of a WTD herd is a complex issue heavily influenced by the perceptions and opinions of individual stakeholders (Tremblay and Côté 2004). Communities may have differing views on whether their local deer are overabundant and the necessity of deer management. For example, hunters often desire more deer encounters, which may differ from the general public's perspective (Raik et al. 2005). Additionally, communities sometimes perceive local WTD populations as too small if residents do not frequently see deer, despite studies indicating that encounter frequency is not necessarily a reliable population indicator (van Etten et al. 1965). Striking a balance between accommodating diverse stakeholder preferences and obtaining broad-scale WTD population control is important when developing sustainable management programs (NDTC 2008).

The success of WTD management coordination initiatives often hinge on stakeholder involvement, acceptance, and support. Previous studies have emphasized that coordination and cooperation among stakeholders are pivotal for effective WTD management efforts (Hall and Gill 2010, Meek 2013). However, achieving this collaborative endeavor is a challenging goal as diverse stakeholder preferences can yield substantial hurdles in identifying common goals (Messmer et al. 1997, Raik et al. 2005, Hall and Gill 2010). Researchers have proposed that management programs should function as mutualistic partnerships among stakeholders, fostering a sense of collective responsibility (Leong et al. 2009). This approach can narrow the gap between public perceptions and the realities of WTD management, leading to a more coordinated system and community that better understands the complexities and trade-offs involved (Messmer et al. 1997, Chase et al. 2000, Leong et al. 2009, Davies and White 2012). Ultimately, the feasibility of management coordination depends on how roles are allocated, responsibilities are adopted, mutual goals and values are defined, and robust communication and trust are established within networks (Davies and White 2012).

Recognizing the need for more inclusive and coordinated deer management efforts, stakeholders have increasingly sought involvement in the decision-making process (Chase et al. 2000, NYSDEC 2018). Concepts such as co-management, where diverse stakeholder groups are involved in negotiating the authority and responsibility of WTD management decisions, represent developments in addressing the complex and conflicting interests associated with WTD management (IUCN 1997, Chase et al. 2000). Co-management has demonstrated positive outcomes, including better informed, more engaged, and more supportive communities when it comes to controversial management decisions (Chase et al. 2000). Researchers have argued that effective management is made possible by encouraging and facilitating stakeholders to voice their opinions (Lynn 2010). Through stakeholder engagement and collaboration, municipalities can select management programs that better align with community preferences.

To manage the challenges associated with overabundant WTD populations in New England, different management techniques have been employed with varying levels of coordination, including both non-lethal and lethal approaches (NDTC 2008, Gamborg et al. 2020). These strategies encompass restoring ecological balances through predator reintroductions (Ripple and Beschta 2004), non-lethal control such as fertility control and translocation (Beringer et al. 2002, Merrill et al. 2006), and lethal methods like hunting and sharpshooting (Heusmann 1973, Woolf and Roseberry 1998, Kilpatrick and David Walter 1999). Among these strategies, hunting (often in the form of recreational or controlled hunts in rural areas) and sharpshooting (professionals hired to cull deer populations in urban areas) represent the most common approaches in reducing WTD densities in the region (Conover 1995, Hansen and Beringer 1997, Figura 2017). Hunters have played a substantial role in both the historical restoration of WTD populations and ongoing management efforts of overabundant populations (Hewitt 2015). When supported by the community, sharpshooting is most often used in urban areas where hunting is rendered unfeasible due to safety restrictions or concerns (DeNicola et al. 2000). Despite the popularity of these strategies, the question remains of whether increased management coordination can improve their efficacy, potentially conserving resources and promoting impacts beyond local areas.

The call for studies regarding the dynamics of management coordination resonates globally (Casebeer 1978, Valdez et al. 2006, Feng et al. 2021). In most places worldwide, formal deer management systems are non-existent (Pérez-Espona et al. 2009). Previous studies have hypothesized that a lack of WTD management coordination, especially across large scales, significantly reduces the chances of decreasing local deer populations (Hall and Gill 2010, Fattorini et al. 2020). Furthermore, other studies have documented that wild deer populations are prone to increase in the absence of coordinated efforts (Finch and Baxter 2007), which could be detrimental depending on community goals. Fattorini et al. (2020) showed that coordinating large ungulate management programs is generally more effective when done at a scale larger than the intended impact area; however, the degree that efficacy improves at larger scales may be relatively small and context dependent.

Some countries have formed international partnerships that aim to enhance cooperation and coordination in wildlife management across nations by focusing on collaborative programs that conserve mutual resources (Valdez et al. 2006). National deer management structures have also been explored, like The Deer Commission for Scotland, that oversees deer management across the country and mitigates conflict when necessary (Deer Commission for Scotland 2001, Pérez-Espona et al. 2009). On a smaller scale, regions like England and Wales have established programs like The Deer Initiative to promote sustainable, coordinated deer management systems in their local areas (The Deer Initiative Limited n.d., Pérez-Espona et al. 2009). These collaborations and initiatives highlight the growing recognition of the importance of coordination in addressing wildlife management challenges on a larger scale. New England has a decentralized management structure, involving various levels of governance from state to municipal entities, often resulting in conflicting objectives (NYSDEC n.d.). This decentralization raises questions about who should be responsible for WTD management, with individual municipalities in some states adopting oversight roles (The New York State Senate 2019).

The literature suggests that a coordinated approach may be necessary in dealing with the complex regional challenges of managing WTD populations. These coordinated efforts can transcend geographic barriers (Hall and Gill 2010), discipline boundaries (Casebeer 1978, Alt et al. 1992), and even cultural differences (Feit 1998), involving a shared commitment to addressing multifaceted challenges through cooperation and conversation. Though previous studies have investigated matters such as sharpshooting (DeNicola and Williams 2008) and hunting (Williams et al. 2013) efficacy, management scale (Fattorini et al. 2020) and area (Van Buskirk et al. 2021) requirements for success, and stakeholder engagement strategies (Chase et al. 2000, Siemer et al. 2004, Leong et al. 2009), none have conducted a case study analysis of WTD management coordination in New England through agent-based model simulation.

This project addresses a pressing problem in the field of wildlife management, specifically concerning the social, ecological, and theoretical dimensions of WTD management coordination in New England. Here, I define the general New England region as including Maine, Vermont, New Hampshire, Massachusetts, Connecticut, Rhode Island, and additionally, New York. Though New York is not typically associated with this region, I am including it because it holds a central position in this research and its implications. As described further in the Methods section, this study focuses on data from New York (NY) and Massachusetts (MA), USA. While the management of deer in New England is intricate and multifaceted, the prevailing objectives typically revolve around the goal of reducing local deer densities. Consequently, this study concentrates on evaluating the effectiveness of municipalities seeking to decrease their local deer densities, though I provide a discussion of alternate viewpoints throughout.

In NY and MA, deer are managed by their state wildlife agencies, the New York State Department of Environmental Conservation (NYSDEC) and MassWildlife, respectively. In both states, the development of Wildlife Management Units (NY) and Wildlife Management Areas (MA) has provided a mechanism for coordinating deer management decisions within the state (Wagner et al. 2010). In 2007, the Integrated Deer Research and Management Program was established in New York to evaluate the role of various lethal and non-lethal deer management strategies, to reduce local deer densities, and to carry out a variety of coordinated management efforts among different municipalities (Boulanger et al. 2014). These implementations exemplify the importance of coordinated efforts in addressing deer management challenges and the need for ongoing research regarding coordination to develop effective and sustainable strategies.

In this study, I propose 3 research questions that address how ecological science, theory, and social science merge together to inform WTD management coordination in New England. In no particular order, the research questions converge to provide a unique investigation into the complexities of deer management coordination in the region (Table 18).

Table 18. This table depicts the research questions and their corresponding objectives, hypotheses, and predictions.

	Question 1	**Question 2**	**Question 3**
Categories	Ecological Science	Theory	Social Science
Questions	What is the relationship between management strategy and WTD density within an isolated town based on an abstract agent-based model analysis of New England towns?	What is the relationship between the spatial scale of WTD management coordination and WTD density in New England based on a theoretical agent-based model analysis?	What is the relationship between WTD management cooperation/ coordination and WTD density in New England based on an abstract agent-based model analysis?
Objectives	Evaluate the relationship between 4 management strategies and WTD density within an isolated town based on analysis of an abstract agent-based model.	Assess the relationship between the spatial scale of WTD management coordination and WTD density based on theoretical agent-based model analysis.	Analyze the relationship between WTD management cooperation/ coordination and WTD density through an abstract agent-based model.
Hypotheses	H_1. The intensity of management efforts within an isolated town negatively correlates with WTD density due to greater efficacy of lethal methods in reducing deer numbers.	H_2. Spatial scale of management positively correlates with WTD density due to increased spatial refugia for deer.	H_3. The level of cooperation and coordination of lethal management methods negatively correlates with WTD density because of increased regional management efficacy.
Predictions	P_1. As management intensity increases, WTD density declines.	P_2. As the spatial scale of management increases, WTD density also increases.	P_3. As management cooperation/coordination increases, WTD density declines.

Through the ecological research question, I seek to understand how different management strategies impact WTD density in New England. My objective is to evaluate the relationship between 4 management strategies (no harvest, sharpshooting, hunting, and both lethal strategies) and WTD density within an isolated town based on analysis of an abstract agent-based model. I hypothesize that the intensity of management efforts within an isolated town negatively correlates with WTD density due to greater efficacy of lethal methods in reducing deer numbers. I predict that as management intensity increases, WTD density declines.

With the theory-based research question, I inquire about the impact of the spatial scale of management on WTD density, where density serves as an indicator of management success. Accordingly, my objective involves assessing the relationship between the spatial scale of deer management coordination and WTD density through a theoretical agent-based model analysis. I hypothesize that the spatial scale of management positively correlates with deer density due to increasing level of spatial refugia for deer, and predicted that as spatial scale increases, deer density also increases. To assess scale dynamics, I designed the model to depict an abstracted version of the New England landscape at 3 spatial scales (Figure 23). Scale 1 represents a single town, where scales 2 is a central town with a layer of surrounding towns, and 3 is a central town with 2 layers of surrounding towns. Scale 1 focuses on dynamics within a single, isolated town, where scales 2 and 3 seek to answer the broader question of how neighboring towns and their management influence each other.

Based on the social science question, I aim to explore to what degree management coordination influences program efficacy in reducing deer populations. My objective is to analyze the relationship between deer management cooperation/coordination and deer density

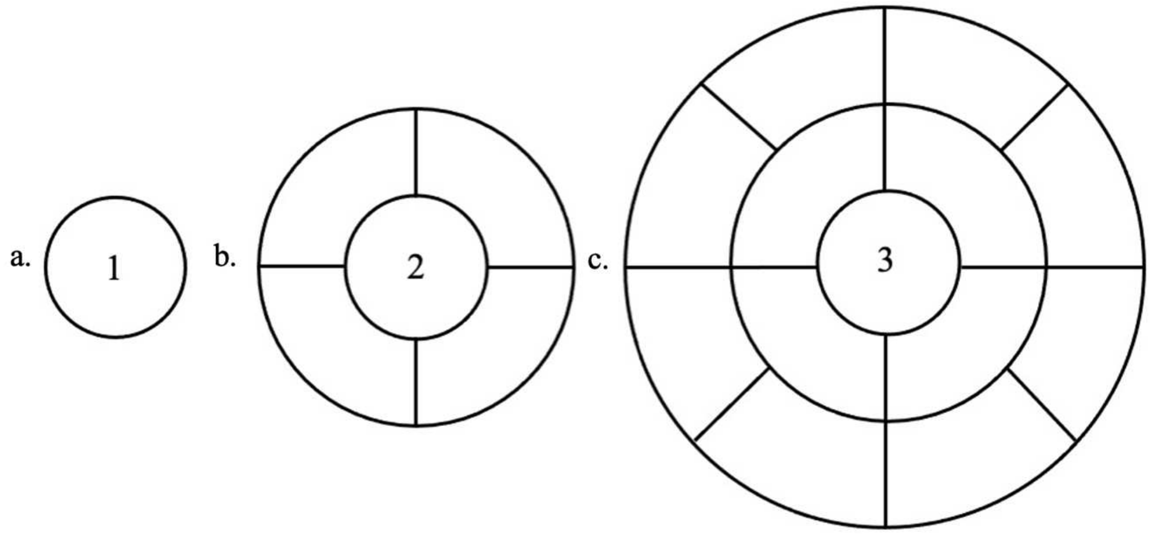


Figure 23. The 3 scales within the abstract model. Scale 1 (a) comprises a single town (*n* = 1), scale 2 (b) includes the central town with an outer ring of 4 neighboring towns (*n* = 5), and scale 3 (c) extends further to incorporate the first 2 scales with an additional layer of 8 surrounding towns (*n* = 13).

through an abstract agent-based model analysis. I hypothesize that the level of cooperation and coordination of lethal management methods negatively correlates with deer density due to increased regional management efficacy. I predicted that as cooperation/coordination of management approaches increases, WTD density declines.

4.3. Methods

4.3.1. Study Area—The broader study team consisted of social and ecological scientists from the University of Wisconsin-Madison, Boston University, Texas A&M University, and Colorado State University. To initiate the project, the team strategically selected 11 focal towns in NY (*n* = 5) and MA (*n* = 6), US (Figure 24) as a platform for their greater initiative of assessing various aspects of these coupled natural-human systems. This selection was informed by preliminary

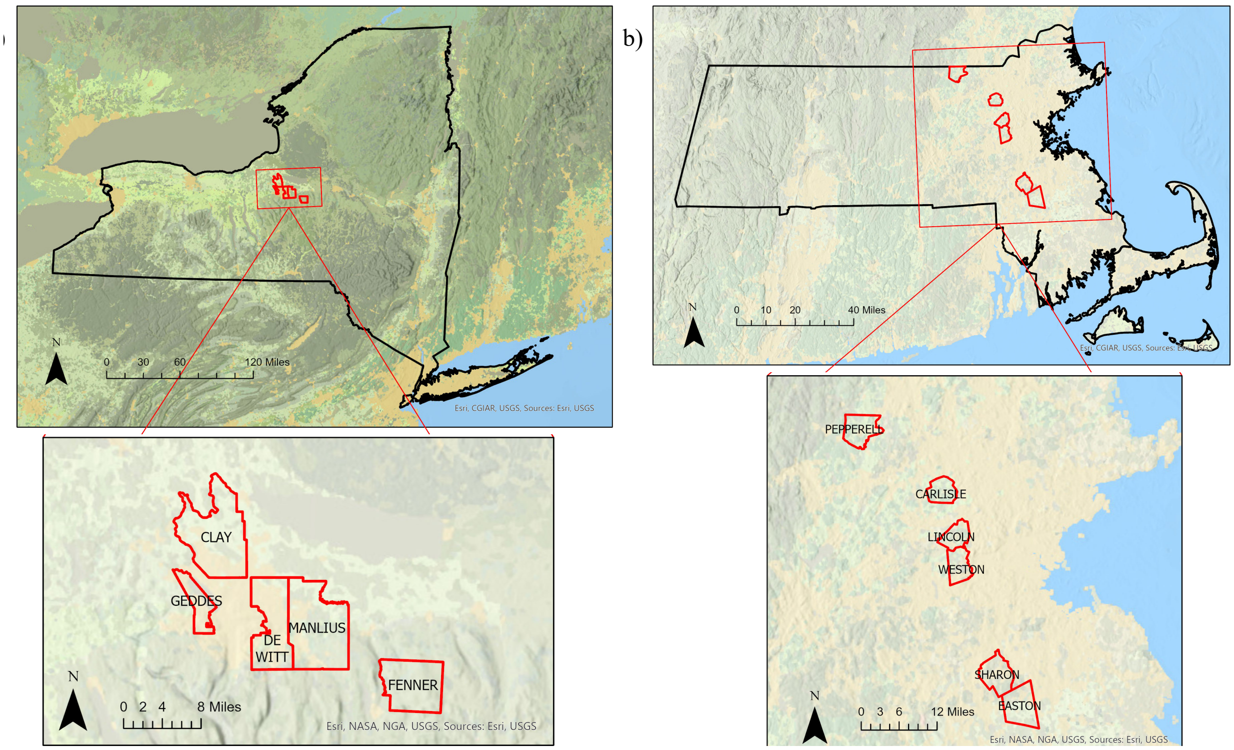


Figure 24. Study Area map depiction of the focal towns (boundaries in red) in (a) New York (n = 5) and (b) Massachusetts (n = 6), USA. The underlying images are from the National Land Cover Database (NLCD 2023).

surveys and extensive interviews with state wildlife agencies including MassWildlife and the NYSDEC. The primary objective behind this selection was to achieve a balance between maximizing the diversity of represented WTD management practices while adhering to the constraints posed by timelines and budgets. Importantly, this approach ensured the novelty of such a broad-scale social/ecological WTD project in this region, while balancing feasibility of the overall project. This town selection encompassed municipalities where WTD management had been actively considered, implemented, or remained entirely unexplored (Table 19)—a deliberate choice to maximize the potential for discerning meaningful patterns (Tuzlukov 2002) within this dynamic and contrasting management environment.

Table 19. A table depicting MA (n = 6) and NY (n = 5) focal towns with landscape context (suburban vs. rural) and WTD management notes (consideration/implementation of management).

State	Townships	Context	Management Notes
MA	Pepperell	Rural	• Pepperell does not have a WTD management plan.
	Carlisle	Suburban	• Carlisle adopted a volunteer bow hunt program in 2018 but suspended it in 2020 due to controversy.
	Lincoln		• Lincoln has not adopted a program but has considered increasing hunting access.
	Weston		• Weston has had a bow hunt program on town lands since 2012 and facilitates hunter access on private lands.
	Sharon		• Sharon is mostly closed to hunting and has high WTD numbers.
	Easton		• Easton is mostly open to hunting with few restrictions.
NY	Fenner	Rural	• Fenner does not have a WTD management plan.
	Manlius	Suburban	• Manlius adopted a maintenance sharpshooting program in 2018, though a village within the town started the program in 2016.
	DeWitt		• DeWitt initiated a sharpshooter program in 2017.
	Geddes		• Geddes adopted a sharpshooting program in 2021 and has conducted resident surveys regarding local WTD.
	Clay		• Clay does not have a WTD management plan.

Both NY and MA have well-documented controversies surrounding WTD management, cooperation of stakeholders, and coordination of towns (Diefenbach and Shea 2011). Within these states, many municipalities have faced challenges regarding the consideration and implementation of various WTD management programs, each characterized by its own degree of success (Dizard and Goble 1995, Berger 2009, Leaver 2012, Pratt 2015, Figura 2017). MA primarily relies on volunteer bow hunts, an approach well-documented in literature (Dizard and Goble 1995, McDonald et al. 2007, Leaver 2012, Pratt 2015), whereas NY employs a broader spectrum of techniques, such as chemical contraceptives (Naugle et al. 2002), sharpshooting (Berger 2009), and sterilization (Boulanger et al. 2012). In terms of predominant weather and vegetation cover, we classified NY and MA as sufficiently similar for comparability within this study (PRISM 2020, NLCD 2019). While the dominant land cover characteristics are largely similar between the 2 states, small differences in land use open opportunities for the exploration of WTD management under various smaller-scale conditions, like those in other regions of the US (NLCD 2019).

4.3.2. Data Collection—To address questions regarding WTD management coordination in New England, the broader team conducted a data collection effort over 4 consecutive years (2019-2023), encompassing both social and ecological dimensions. The fusion of ecological and social data provided a robust foundation for the model, promoting the applicability of findings and conclusions related to WTD management coordination in the region. Refer to the previous chapters for a more in-depth review of data collection methods related to previous model development. I synthesized the abstracted model in this chapter by obtaining average estimates from all focal towns models of Chapters 2 and 3. The objective was to represent the average dynamics of the New England WTD management system to serve as a foundational basis in addressing theoretical implications regarding coordination.

4.3.3. Agent-based Model—In the context of agent-based modeling, an "agent" is an autonomous, decision-making entity that interacts with its environment and other agents to simulate complex systems and emergent behaviors (Wilensky and Rand 2015). According to Wilensky and Rand (2015), the primary objective of agent-based modeling is to address specific research inquiries and gain a deeper understanding of outcomes. This strategy does not aim to encompass every facet of a phenomenon; rather, it focuses on the exploration of areas of interest, with the intention of stimulating conversation rather than simulating a system perfectly (Resnick 1994). I created a model description based on the established ODD (Overview, Design concepts, Details) protocol for evaluating agent-based models, initially introduced by Grimm et al. (2006) and later updated (2010, 2020). The role of this standardized protocol promoted reproducibility in my approach, thereby lending scientific credibility to the model process and outcomes (Wilensky and Rand 2015). See Appendix C for a complete model description, and below for a summary.

Using similar WTD agent-based models as a foundation (Xie et al. 1999, Van Buskirk et al. 2021), I parameterized and interpreted this model in a program called NetLogo (Wilensky 1999). Compared to the models in previous chapters, this one is more abstract in nature as realistic heterogeneity and variation is drastically reduced to capture underlying theoretical dynamics. The broader purpose of this abstract agent-based model design is to construct interpretations relevant to the theoretical underpinnings of WTD management coordination. Specifically, the aim of this model is to assess the coordination dynamics of WTD management through time and across 3 spatial scales, creating a theoretical representation of the New England WTD management system.

The model flow consists of 3 phases, where the user 1. sets up the landscape, 2. runs the simulations, and 3. learns from observed outcomes (Figure 25). Once the landscape is created and agents are placed upon it during initialization, the model interface then depicts a unique landscape of the scenario, showing abstracted spatial features such as urban areas and huntable regions. Average numbers of deer, hunters, and sharpshooters are depicted based on model outcomes of previous chapters. Agents move and interact with each other and their shared environment during the run phase according to agent-specific attributes and behaviors. The key interactions are between deer-deer during the rut (i.e., reproduction rates), hunter-deer during the hunting season (e.g., harvest rates), and sharpshooter-deer during the culling timeframe (e.g., cull rates). WTD density is tracked throughout the

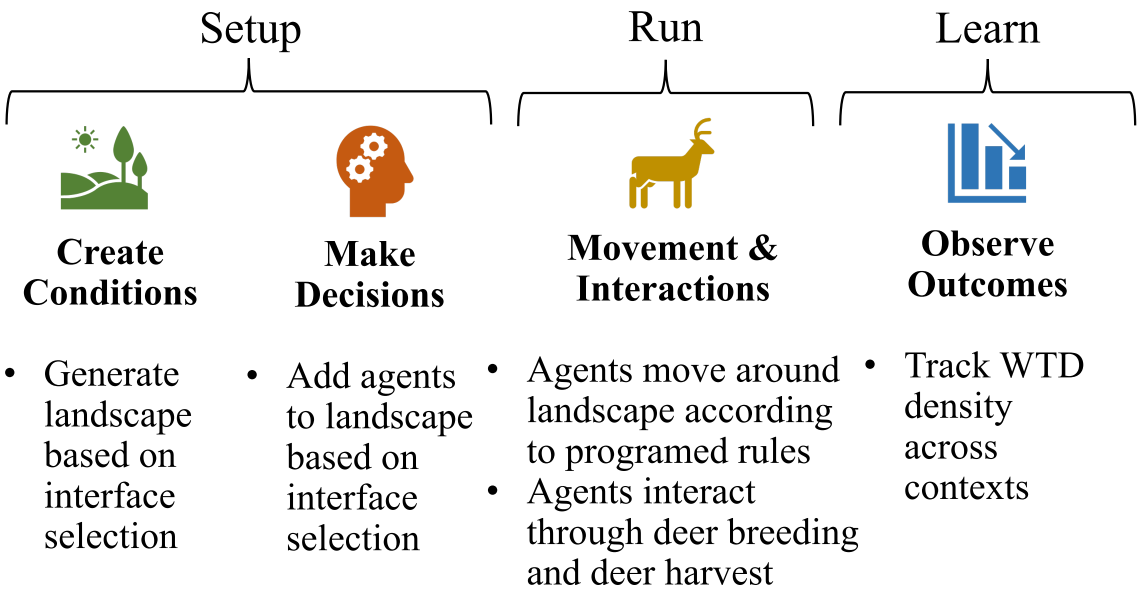


Figure 25. A graphical depiction of the model flow process, including 1) setup, 2) run, and 3) learn phases (Adapted from Monlezun 2022).

simulation, ultimately informing results and addressing research questions during the learn phase of the model process.

During initialization, there are 3 model parameter categories where the user: 1. picks a central town management strategy, 2. selects the scale, 3. chooses the similarity threshold for scales 2 and 3, and 4. determines values for agent densities and access levels (Figure 26). During the SETUP procedure, the strategy, scale, and similarity parameter selections inform the model environment, and the agents are placed upon the landscape based on agent parameter selections. Deer are randomly placed on the landscape with a slight favoring for non-huntable locations, hunters are placed in huntable regions, and sharpshooters are placed in urban areas. The last phase of this procedure includes forming deer social structures in the environment to reflect realistic social dynamics. In the GO procedure, time is tracked, deer are aged, non-harvest mortality occurs, agents move, and deer go through annual behavioral submodels that include a

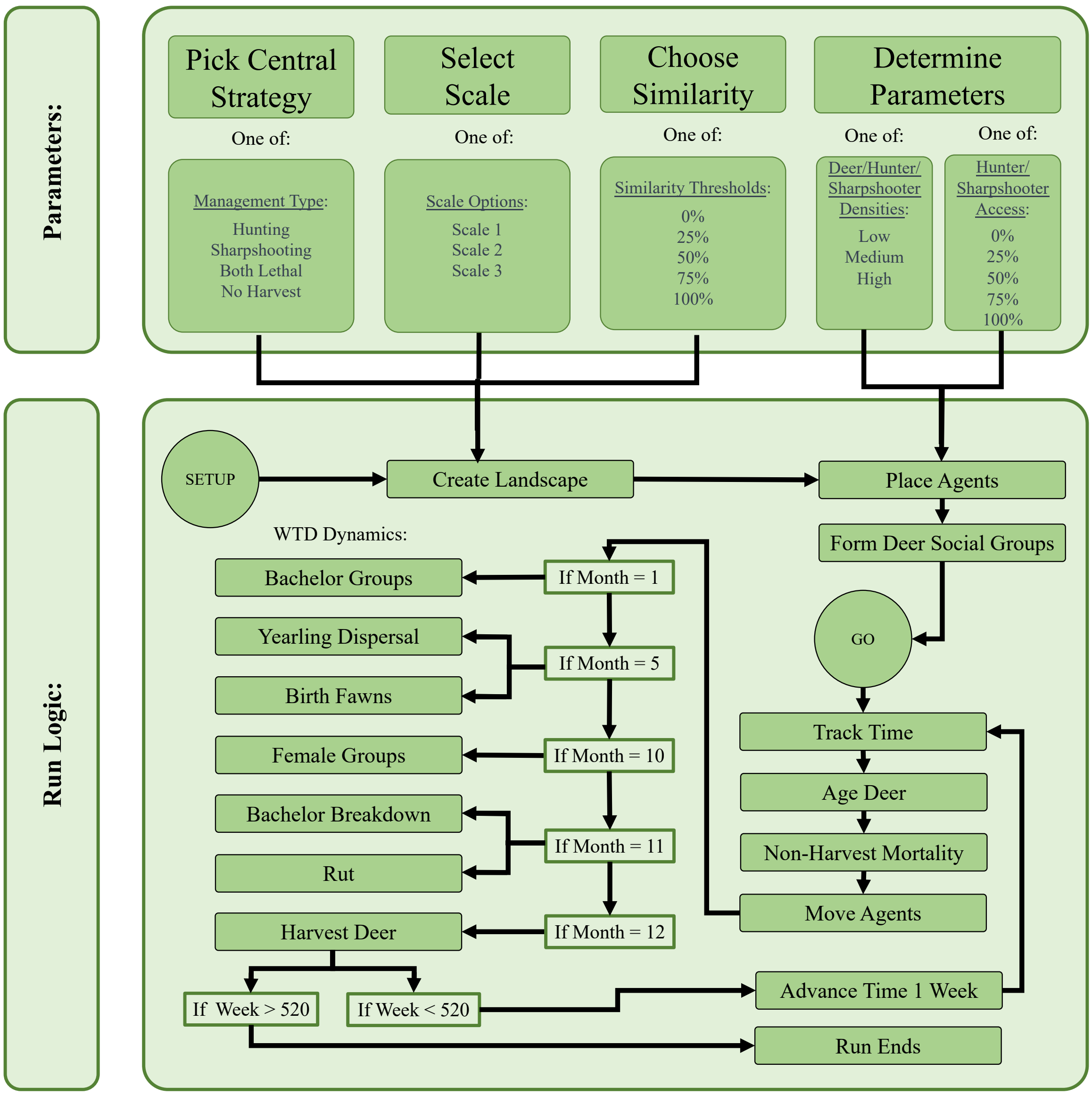


Figure 26. A flow chart depicting the parameter options and resulting run logic for the theoretical agent-based model (Adapted from Monlezun 2022).

sharpshooting phase. The simulation ends when 10 years has elapsed, otherwise time advances by 1 week and the GO procedure repeats.

The model has a resolution of 900 m^2 (30 m x 30 m patches) and contains towns approximately 2.7 mi^2 (7.0 km^2), lending to a model landscape of between 2.7 mi^2 (7.0 km^2) and

29.9 mi^2 (77.5 km^2), depending on the scale. Though the average focal town is, in reality, roughly 23 mi^2 (59.6 km^2), this resolution adjustment allows the models to run efficiently, as processing a larger landscape with an increased number of agents would otherwise result in impractical computational delays. See Figure 27 for a visual example of the model on the

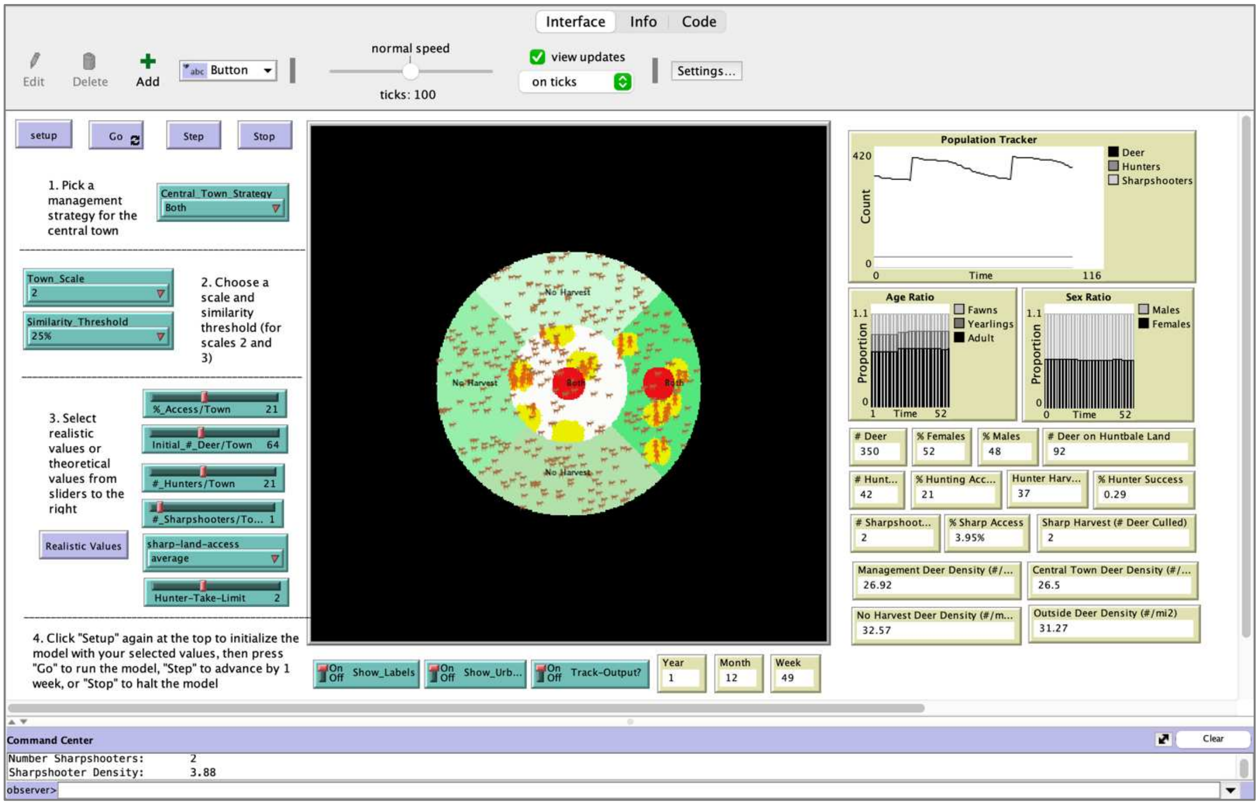


Figure 27. The theoretical model interface in NetLogo, showing scale 2 with hunting and sharpshooting at 25% similarity, along with relevant monitors and user controls on the interface. Yellow represents huntable areas and red represents urban zones.

NetLogo interface. All towns have the same agent densities and management land areas (for sharpshooting and hunting), contain the same land cover, and represent the same areas such that the only changing factor is the town management strategy implemented. Operating under a weekly timestep (starting in January) and spanning a 10-year timeframe, the model encompasses 3 agent types: deer, hunters, and sharpshooters, each with distinct attributes and behaviors. These agents interact within the landscape, with deer moving freely year-round, hunters confined to huntable areas from October through December, and sharpshooters limited to urban zones from January through March. When deer come within specific distances of hunters (approximately 0.5 mi/0.8 km) or sharpshooters (roughly 0.2 mi/0.3 km) during their respective seasons, the deer are harvested in response to estimated probabilities. This agent-based perspective is central to the model, guiding the emergence of dynamic outcomes.

I based the model parameterization on average values from all models in previous chapters. For example, I used the average hunter density among all towns from Chapters 2 and 3 to guide dynamics in the abstracted model of this chapter. See Table 20 for a breakdown of key parameters. For the previous chapters, I relied on the most recent parameter estimates possible from state wildlife agencies, the literature, and expert opinion. I used average estimates of sharpshooting dynamics (access, sharpshooter density, and harvest density) from municipalities in the study area that implemented and recorded sharpshooting efforts. To simulate urban areas, each town within the model includes a circular zone in the center of the town, symbolizing areas accessible to sharpshooters. Likewise, to mirror the real-world heterogeneous distribution of hunting access, every town has 5 randomly placed clusters representing open hunting access in various locations.

4.3.4. Scenarios and Analyses—In all scenarios, the central town adopts 1 of 4 possible management strategies: 1) no harvest, 2) hunting, 3) sharpshooting, or 4) both hunting and sharpshooting. For scales 2 and 3, there are similarity thresholds that indicate the percentage of surrounding towns that adopt the same management strategy as the central town. Similarity thresholds are irrelevant for scale 1 due to it being a single, isolated town landscape. These thresholds can be systematically varied at 100%, 75%, 50%, 25%, and 0%, ensuring that the

Table 20. Theoretical agent-based model parameters, definitions, values, and sources. Values are averages of all focal towns in previous chapters.

Parameter	Description	Value	Source(s)
Female Deer (%)	Percent female deer relative to total deer in the population at time of data output (January 1).	58.0	Coe et al. 1980, Boulanger et al. 2012
Male Deer (%)	Percent male deer relative to total deer in the population at time of data output (January 1).	42.0	Coe et al. 1980, Boulanger et al. 2012
Fawns (%)	Percent fawns relative to total deer in the population at time of data output (January 1).	28.8	Collier 2004
Yearlings (%)	Percent yearlings relative to total deer in the population at time of data output (January 1).	23.8	Collier 2004
Adults (%)	Percent adults relative to total deer in the population at time of data output (January 1).	47.5	Collier 2004
Deer Population Growth (%)	Realized deer population growth from annual spring births with hunting present.	30.0	Norton 2015, Expert Interview
Fawn Annual Non-Harvest Mortality (%)	Annual non-harvest mortality percent for fawns relative to deer population.	69.0	Nelson and Mech 1986
Yearling Annual Non-Harvest Mortality (%)	Annual non-harvest mortality percent for yearlings relative to deer population.	22.5	Nelson and Mech 1986
Adult Annual Non-Harvest Mortality (%)	Annual non-harvest mortality percent for adults relative to deer population.	22.5	Nelson and Mech 1986
Fawn/Yearling Harvest (%)	Annual percentage of fawns and yearlings harvested by hunters relative to the total deer population.	10.0	Boulanger et al. 2012
Adult Harvest (%)	Annual percentage of adults harvested relative to the total deer population.	90.0	Boulanger et al. 2012
Buck Harvest (%)	Annual percentage of bucks harvested relative to the total deer population.	50.0	Boulanger et al. 2012
Sharpshooter Harvest Density (#/mi^2)	Annual density of deer culled by sharpshooters when implemented, based on most recent average of 3 towns.	11.8	Data from NYSDEC
Sharpshooter Density (#/mi^2)	Sharpshooter density when implemented in each focal town, based on most recent average of 3 towns.	3.9	Data from NYSDEC
Town Area (mi^2)	Average area of focal towns (27.3 mi^2) divided by 10 (for practicality*)	2.7	GIS
Hunting Access (%)	Average estimated percent open hunting access for all focal towns, based on state and local setbacks and restrictions.	21.0	GIS
Hunters (#)	Average hunter number per town* based on licenses sold in each town.	43	NYSDEC 2019, MassWildlife 2020

Table 20 (*Continued*). Theoretical agent-based model parameters, definitions, values, and sources. Values are averages of all focal towns in previous chapters.

Parameter	Description	Value	Source(s)
Hunter Density (#/mi^2)	Average hunter density estimates of town based on licenses sold in each town.	15.6	NYSDEC 2019, MassWildlife 2020
Initial Deer (#)	Average initial deer population per town* based on most recent estimates.	407	NYSDEC 2019, MassWildlife 2020
Deer Density (#/mi^2)	Average town-level deer density based on population estimate and town area.	17.5	NYSDEC 2019, MassWildlife 2020
Harvest Mortality (%)	Average deer harvest mortality according to population and harvest estimates.	20	NYSDEC 2019, MassWildlife 2020
Antlerless Harvest Density (#/mi^2)	Average annual harvest density of antlerless deer (females and fawn males).	1.36	NYSDEC 2019, MassWildlife 2020
Buck Harvest Density (#/mi^2)	Average annual harvest density of bucks.	2.24	NYSDEC 2019, MassWildlife 2020

*I reduced population numbers (#) by a factor of 10 while preserving percentages (%) and densities (#/mi^2) to maintain model feasibility.

resulting percentages remain whole numbers to maintain experimental rigor (a town cannot have 0.5 of a management strategy). Which surrounding towns share management is randomly generated during each model run. If a town does not share the same management as the central town, they adopt a no harvest strategy to represent commonplace baseline characteristics. For example, if I assess impacts at scale 2 (1 central town and 4 surrounding towns), the central town adopts hunting, and there is 50% similarity, that means 2 of the adjacent towns also adopt hunting, while the other 2 do not implement a harvest strategy. Refer to Figure 28 for visual examples.

A nuanced but relevant point is that when a central town has no harvest as a management strategy, the surrounding towns also adopt no harvest despite the similarity threshold. The purpose of this is to not stray from the research questions, and I deemed it unnecessary to evaluate all combinations of surrounding management when the central town implements no harvest. Neighboring towns emulating the central town adopt no harvest. In other words, this coordination effect is already captured in the other scenarios and rendered this exploration

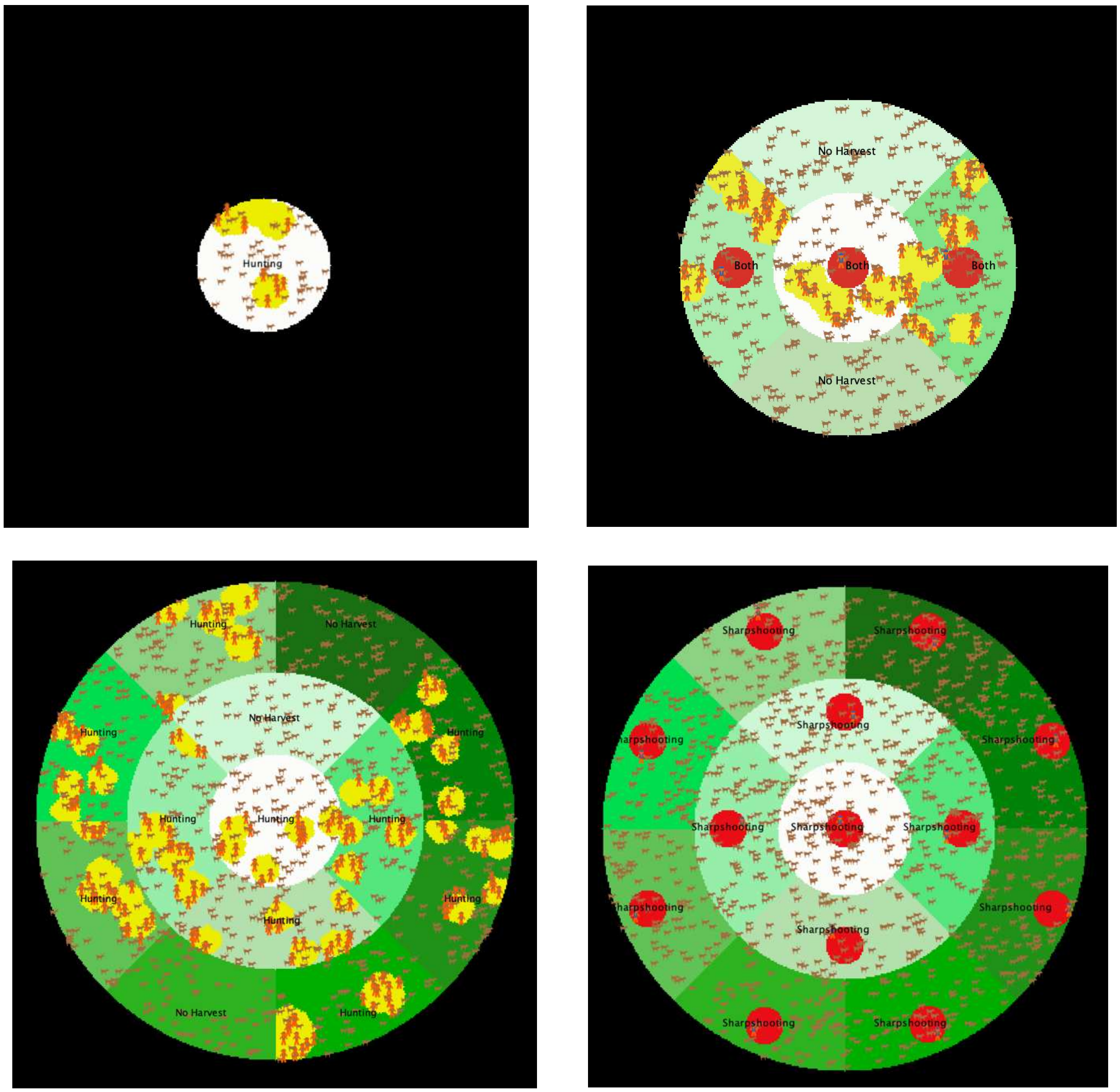


Figure 28. The theoretical model landscapes in NetLogo, showing examples of a) scale 1 with hunting, b) scale 2 with hunting and sharpshooting at 25% similarity, c) scale 3 with hunting at 75% similarity, and d) scale 3 with sharpshooting at 100% similarity. Yellow represents huntable areas and red represents urban zones accessed by sharpshooters.

irrelevant. The analyses explore the deer density within the central town compared to the combined density in surrounding towns, helping to identify the impact of coordination among neighboring towns on the central town's deer population (Figure 29*a*-*b*). Also for scales 2 and 3,

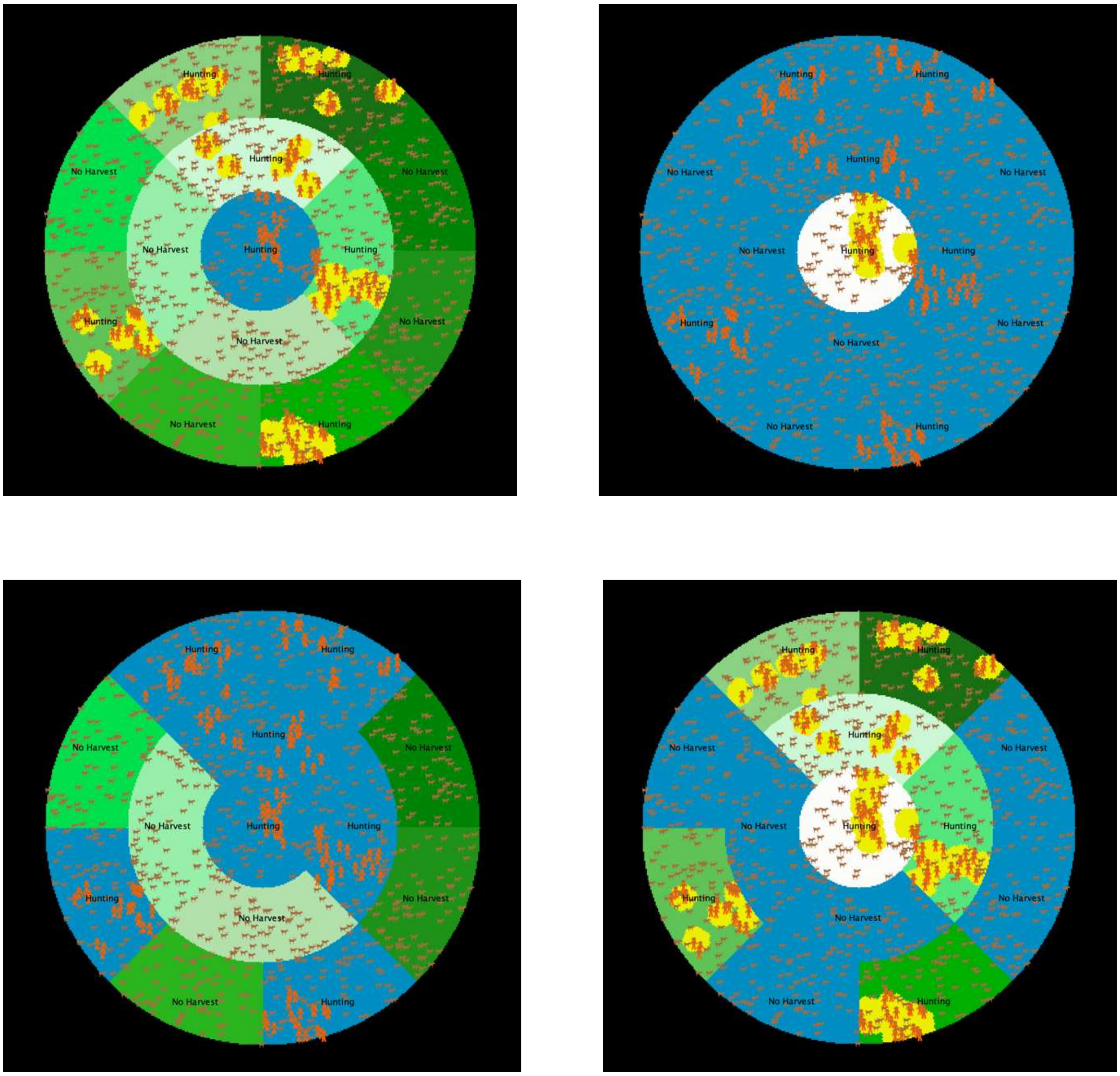


Figure 29. An example of Scale 3 with 50% management similarity of hunting, showing (in blue) where I generated estimates to compare (a) deer density in the central town against (b) deer density in surrounding towns, and (c) deer density in towns with lethal management against (d) deer density in towns with no harvest implemented.

I investigated the deer density in towns that implemented lethal management compared to towns where no harvesting methods were employed to assess spatial density impacts (Figure 29*c*-*d*). The cross-referencing of scales, similarity thresholds, and central management strategies resulted in 60 unique simulation scenarios (Table 21, Figure 30). I ran each scenario the standard 30

Table 21. Scenarios for management coordination assessment (*n* = 36). The first column depicts the variable and unit, and the second column represents management coordination parameters.

	Management Coordination Assessment
Scale	1, 2, 3
Similarity Threshold (%)	0, 25, 50 75, 100
Central Management Strategy	No Harvest Hunting Sharpshooting Both Lethal
Deer Density (#/mi²)	Average (27.8)
Hunter Town Density (#/mi²)	Average (9.3)
Hunting Land Access (% of Town)	Average (21)
Sharpshooter Density (#/mi²)	Average (1)
Sharpshooter Land Access (% of Town)	Average (8)

times to obtain average results and standard errors before interpretation (*n* = 1,800 simulations; Wilensky and Rand 2015).

Throughout the modeling process, analyses took the form of heuristic and quantitative techniques along with specific methods to ensure the model produced meaningful patterns for valid reasons (Railsback and Grimm 2019). Verification (e.g., debugging) confirmed the model was running according to its intended purpose, while validation ensured that the correct

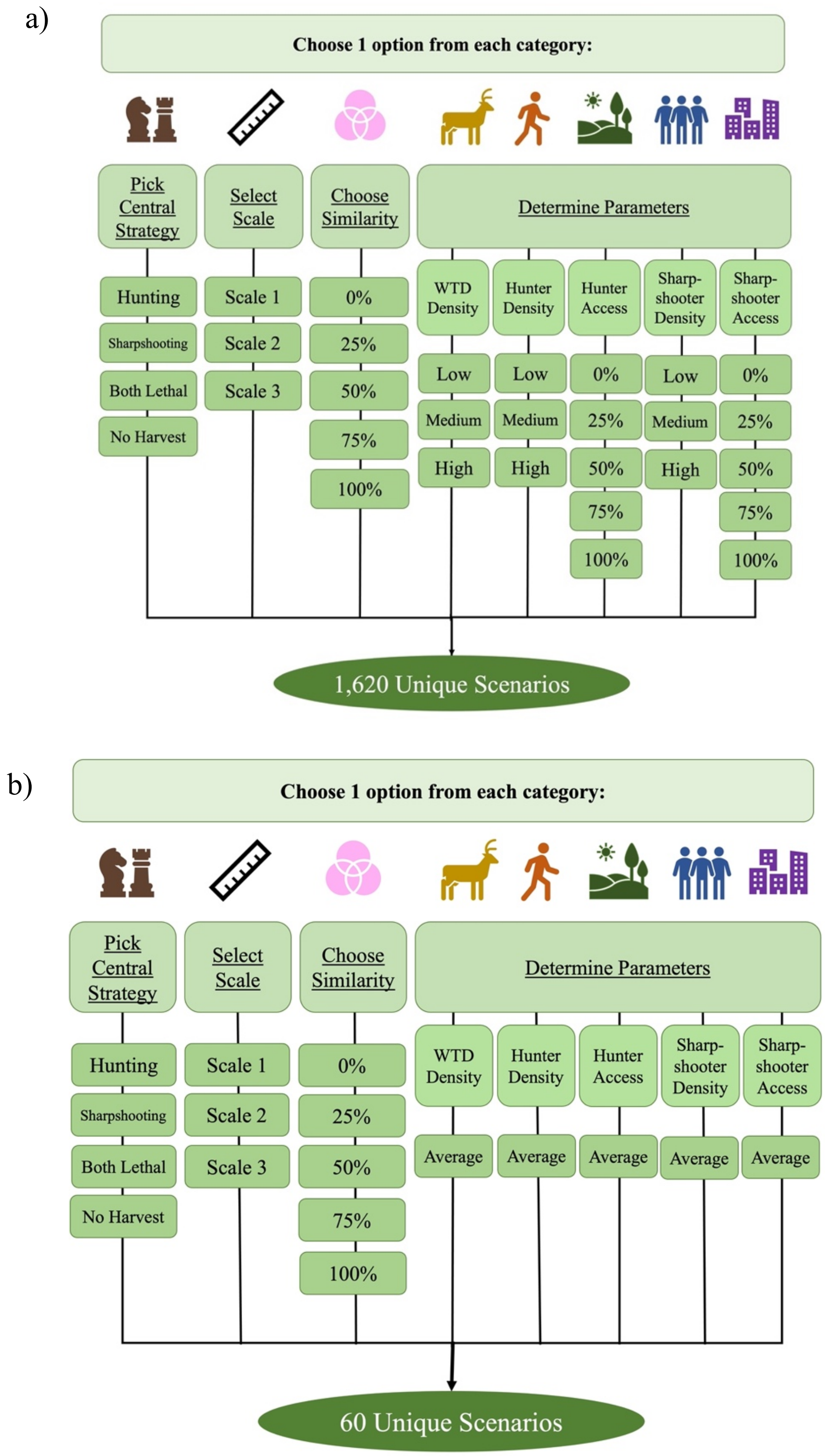


Figure 30. A graphical depiction of the model processes, including the possible parameter selections and the subsequent unique scenarios for a) the user, and b) this chapter's analysis (Adapted from Monlezun 2022).

conceptual model aligned with observed phenomena (Wilensky and Rand 2015, Marshall 2016). Similarly, with the aim of transferring insights to the real-world, I employed pattern-oriented-modeling techniques to promote the representation of the actual system's properties, mechanisms, and behaviors (Rand et al. 2011).

To address Research Question 1 regarding management impact on deer density (ecological), I created a graph of simulation outcomes that compared the efficacy (i.e., ability to reduce local WTD densities) of simulated management strategies (or lack thereof) within a single town. To address Research Question 2 regarding spatial scale (theory), I made a series of graphs that depicted the relationship between spatial scale and WTD density. To address Research Question 3 regarding coordination (social), I crafted an additional series of graphs that evaluated the relationship between cooperation/coordination of management practices and regional WTD density. I created all graphs in Microsoft Excel (2021), and for clarity to US WTD managers, I largely adopted imperial units (e.g., # deer/mi^2) in this study (Kelly and Ray 2019).

4.4. Results

4.4.1. Research Question 1 (Ecological)—The graph plotting WTD density against management strategy depict a negative correlation between the 2 variables (Figure 31). Expectedly, in the absence of management (no harvest) at scale 1, the town's deer density remains relatively high, with a recorded average value of approximately 70 deer/mi^2 (27 deer/km^2). Historically, deer populations at these densities have prompted some communities to implement control programs. The introduction of sharpshooting at scale 1 leads to a slight reduction in final deer density, resulting in roughly 54 deer/mi^2 (21 deer/km^2). Hunting on its own as a management strategy in

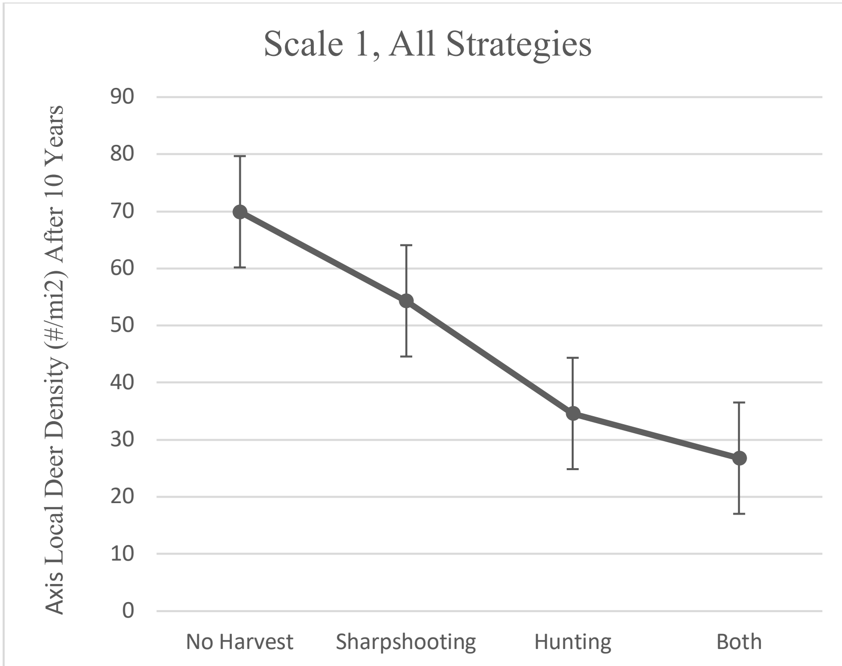


Figure 31. Deer density after 10 years, scale 1**,** depicting the resulting WTD densities (#/mi^2) after 10 years of simulations for a single town under paradigms of no harvest (70 deer/mi^2), sharpshooting (54 deer/mi^2), hunting (35 deer/mi^2), and both sharpshooting and hunting (27 deer/mi^2).

a single town decreases local deer densities to about 35 deer/mi^2 (14 deer/km^2), only slightly higher than the initial density. When both sharpshooting and hunting are combined in a coordinated effort, the town achieves the lowest deer density among all scenarios, with an average estimate of around 27 deer/mi^2 (10 deer/km^2). Thus, at scale 1, the strategy of combining sharpshooting and hunting is the only scenario that reduces local deer densities from the initial density of 28 deer/mi^2 (11 deer/km^2).

4.4.2. Research Question 2 (Theory)—The graphs reveal no correlation (slope of zero) between increasing spatial scale and deer density at 100% coordination (Figure 32), and a negative correlation at all other similarity thresholds (Figure 33). Though the impact from each lethal management type varies, the effect of that strategy does not differ between scales when

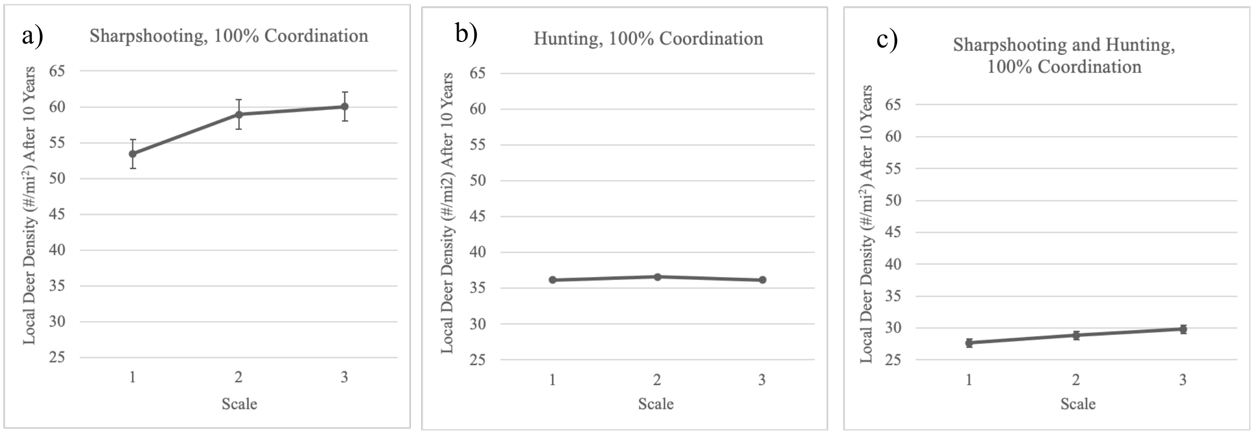


Figure 32. A scale impact comparison that depicts final deer density (#/mi^2) in towns with management at each scale under 100% management similarity (coordination) with scenarios examining (a) sharpshooting, (b) hunting, and (c) both sharpshooting and hunting. Standard deviation bars are depicted but may be too small for visibility.

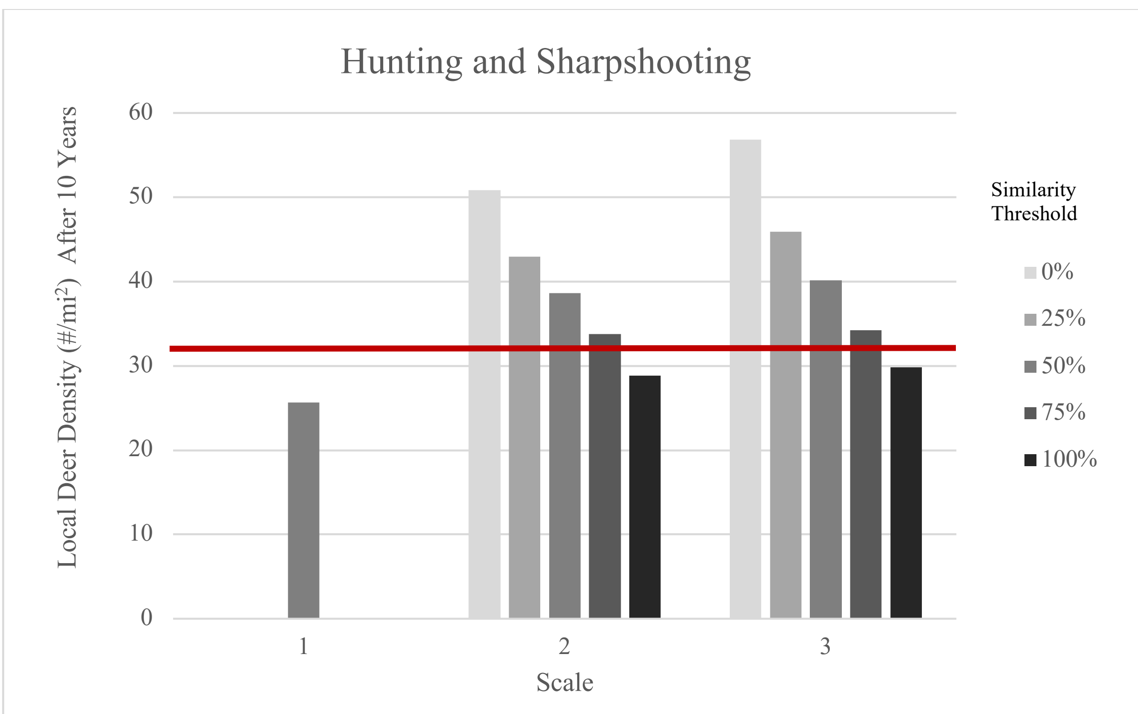


Figure 33. A scale impact comparison that depicts final deer density after 10 years (#/mi^2) compared to scale and similarity thresholds (darker with increasing similarity). The red line indicates the initial WTD population, and only scale 1 and scales 2 and 3 at 100% similarity resulted in reduced WTD densities.

there is 100% management coordination. In other words, the impact of each strategy remains relatively similar irrespective of the spatial scale under paradigms of 100% similarity (i.e., hunters have the same impact at scale 1 as they do at scales 2 and 3 when considering a constant level of coordination). These results demonstrate that, when coordination is at 100%, management effect is consistent at all scales, but when coordination is less than 100%, the impact of management is not sufficient to reduce regional WTD densities.

4.4.3. Research Question 3 (Social)—The graphs demonstrate a negative correlation between increased levels of cooperation/coordination and regional WTD density (Figure 33). The graphs show that as cooperation and coordination levels increase, regional WTD densities decreases. This pattern is consistent across various scenarios of 100% coordination, including hunting, sharpshooting, and a combination of both lethal methods. The same trend is observed when comparing deer density in towns with management to towns without (Figure 34), as well as when comparing central town density to surrounding town density (Figure 35). Across all strategies at scales 2 and 3, there's a slight reduction in deer density as coordination among towns increases from 0% to 100%, both for managed and unmanaged areas. Comparing deer densities within the central town to the collective density of all other towns at scales 2 and 3 also shows consistent decreasing trends. Implementing sharpshooting or hunting alone doesn't reduce deer density below its initial level. However, when both sharpshooting and hunting are combined at scales 2 and 3 with 100% coordination, there is a reduction in deer density.

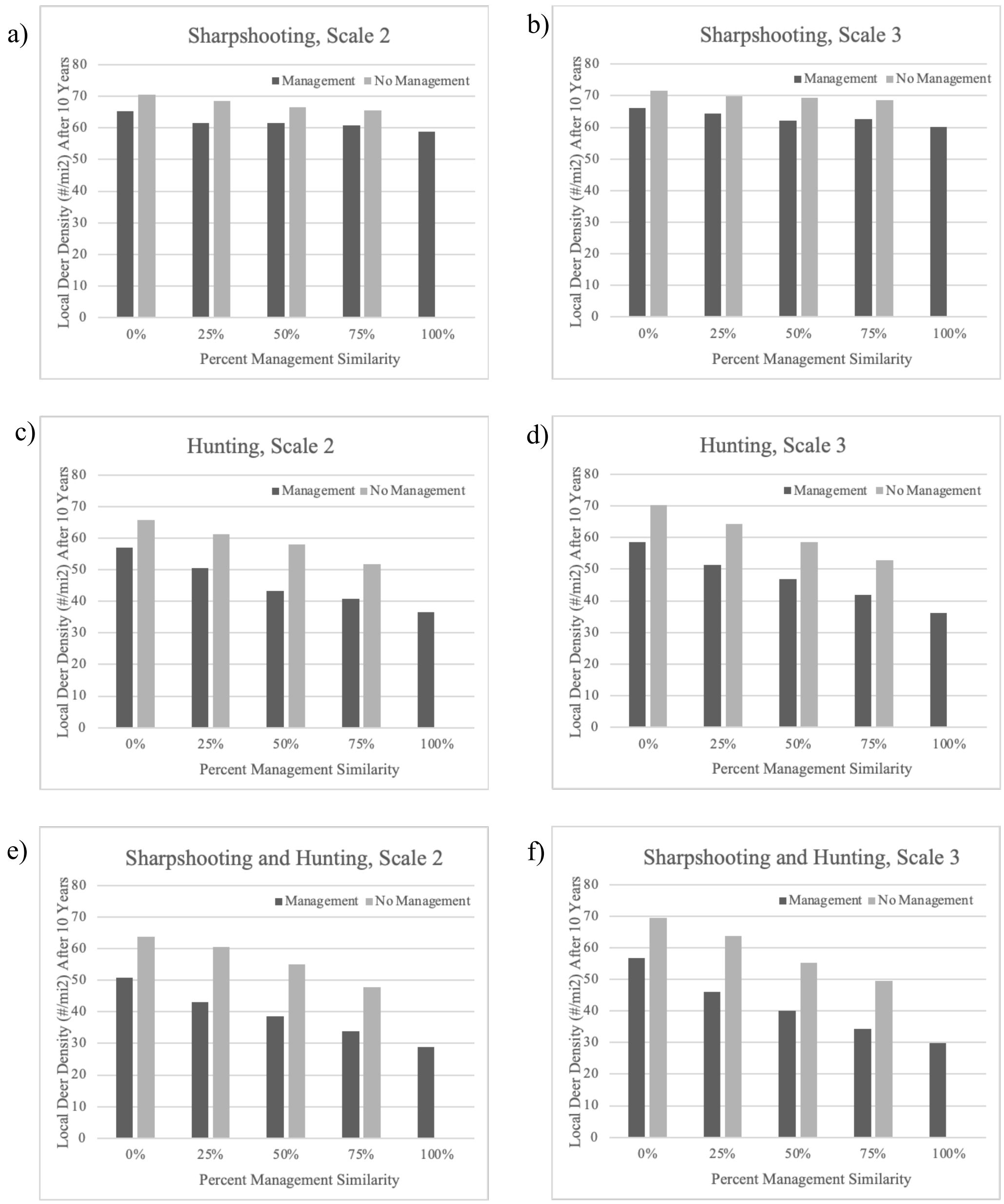


Figure 34. Management versus no management density, scales 2-3 depicting the WTD densities (#/mi^2) in towns with management (hunting, sharpshooting, or both) versus the WTD density in towns without management (no harvest) at scales 2 (left) and 3 (right) under various similarity thresholds (0%, 25%, 50%, 75%, 100%) when (a-b) sharpshooting, (c-d) hunting, and (e-f) both sharpshooting and hunting were the central town strategy (standard error bars omitted due to small size).

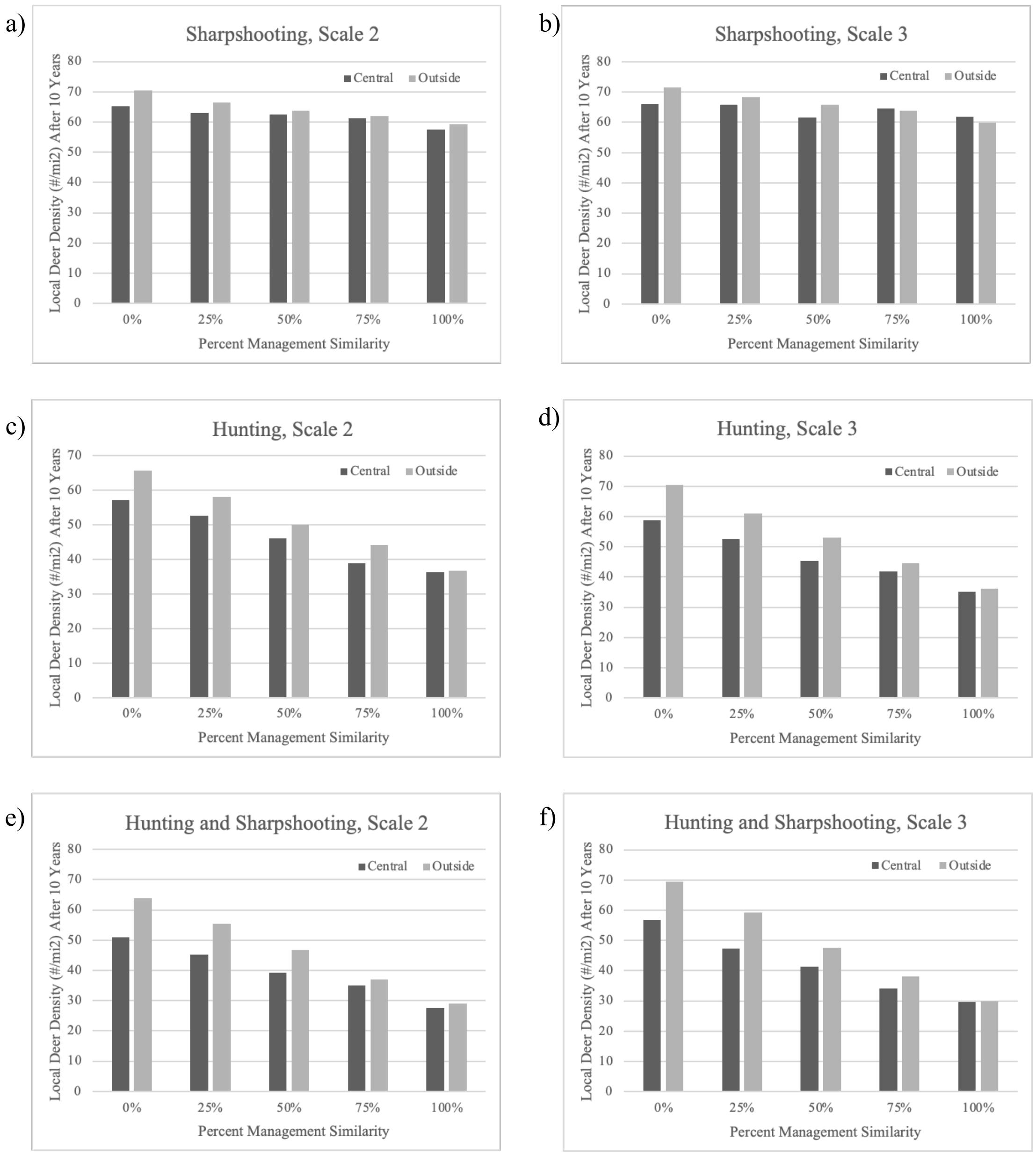


Figure 35. Density of central town versus surrounding towns, scales 2-3 depicting the WTD densities (#/mi^2) within the central town versus the collective WTD density of the surrounding towns at scales 2 (left) and 3 (right) under various similarity thresholds (0%, 25%, 50%, 75%, 100%) when (a-b) sharpshooting, (c-d) hunting, and (e-f) both sharpshooting and hunting were the central town strategy (standard error bars omitted due to small size).

4.5. Discussion

Through this research, I aimed to assess the relationships between management strategy, spatial scale, level of management coordination, and WTD density in New England. I sought to investigate the ecological, theoretical, and social dimensions of this system, ultimately aiming to explore the spatiotemporal dynamics surrounding coordination in shaping effective WTD management in the region.

4.5.1. Research Question 1 (Ecological)—The results demonstrate that the intensity of management efforts negatively correlates with WTD density. As the intensity of management increases, WTD density declines (Figure 31). I assessed the management strategies independently at scale 1, focusing on theoretical dynamics within an isolated town. Combining sharpshooting and hunting is the sole scenario considered that effectively reduces local WTD density below starting levels of 28 deer/mi^2 (11 deer/km^2). Importantly, this does not imply that sharpshooting is less effective than hunting. Rather, with this abstracted model, I aimed to evaluate the current dynamics of WTD management in New England. Hence, these results reflect the average dynamics of the current WTD management system in the region. They imply that, on average, hunting appears to have a more widespread impact on WTD population control in the region compared to sharpshooting. When it comes to sharpshooting efficacy, as explored in Chapter 3, its impact can be greater than hunting depending on the level of access. The substantial reduction in deer density when sharpshooting and hunting are used together underscores the potential for towns to effectively control WTD populations by implementing multiple strategies in unison. This suggests that a diversified approach, which leverages various management strategies and tools, can be highly effective in achieving desired ecological and social outcomes, such as reduced human-deer conflicts and ecological restoration (Conover

1995, Warren 2000, Doerr et al. 2001, Beringer et al. 2002, Tanner et al. 2014). These results support my ecological hypothesis that (H_1) the intensity of management efforts within an isolated town negatively correlate with WTD density due to greater efficacy of lethal methods in reducing deer numbers.

4.5.2. Research Question 2 (Theory)—The outcomes reveal the positive correlation between spatial scale of management implementation and WTD density (Figure 33). As the spatial scale of management increases, WTD density also increases (Figure 33). The results suggest that, when considering the same level of coordination across a 10-year timeframe, resulting regional WTD density is lower at smaller spatial scales. In the model, this result may be contributed to the increasing representation of spatial refugia for deer as scale increases (Storm et al. 2007). Furthermore, the difficulty of coordinating WTD management can also increase at greater spatial scales.

The heterogenous distribution of deer across landscapes results in inconsistent deer-related impacts and human-deer interactions between communities. Stakeholders often hold divergent preferences about how WTD should be managed, shaped by their distinct interactions and experiences with local deer. As the scale of management increases, encompassing larger regions, this complexity amplifies. As more stakeholder groups become involved, each rooted in their unique contexts, it becomes Increasingly difficult to find common ground in management preferences. While consensus may appear at the town scale, management efforts at greater spatial scales demonstrate the trade-off between regional control of WTD populations and accommodating the diverse preferences of stakeholders from different communities. Balancing these aspects presents an intricate challenge, though there are strategies to promote cohesion and facilitate the acceptance of management approaches, such as stakeholder inclusion at all stages of the decision-making process. These outcomes support my theoretical hypothesis that (H_2) the spatial scale of management implementation positively correlates with WTD density due to increased spatial refugia for deer.

4.5.3. Research Question 3 (Social)—The results demonstrate that the level of cooperation and coordination of lethal management negatively correlates with WTD density. As lethal management cooperation and coordination increase, WTD densities decline. This pattern is consistent when comparing resulting WTD densities in 1. the entire region (Figure 33), 2. towns with and without management (Figure 34), and 3. the central town versus the surrounding towns (Figure 35 35). Reduced regional deer density demonstrates the role of small-scale coordination in dictating large-scale outcomes. Previous studies have reached similar conclusions, indicating that enhanced coordination can result in lower regional deer densities across contexts (Casebeer 1978, Alt et al. 1992, Feit 1998, Valdez et al. 2006, Pérez-Espona et al. 2009, Feng et al. 2021). Higher levels of coordination resulting in lower deer densities in towns with and without active management highlights the direct and indirect effects that lethal management can have in areas without management implementation. This further suggests that not all municipalities need to be involved in lethal management to have a regional population effect on WTD. More coordination leading to lower central town WTD densities demonstrates that as collective management efforts increase, deer densities in the central town decrease, underscoring the role of regional coordination in managing local deer populations.

Coordination not only impacts WTD density but can also influence the levels of public support and acceptance, with outcomes varying depending on the context and the strategy's alignment with community preferences. For example, if sharpshooting is implemented in a town where it is met with resistance from residents who do not support such measures, it can lead to conflict and discontent among the community (Siemer et al. 2004). In such contexts, coordination may inadvertently intensify public disdain, as it could be perceived as overriding local preferences and imposing an unsupported management strategy (Smith 2009). This exemplifies the trade-off between broad-scale WTD population control and accommodating diverse community interests.

However, the model results imply a possible shift in opportunities as coordination efforts intensify. When towns collaborate and implement more intensive lethal strategies across broad scales, their collective actions can lead to lower regional WTD densities. This initial decrease sets the stage for potentially exploring alternative, less intensive methods. For example, the literature demonstrates that fertility control programs are often only successful with small deer populations. If local deer densities become within feasibility margins after regional coordination efforts, transitioning to non-lethal methods may become a realistic prospect. This exemplifies how greater coordination can broaden the horizons of WTD management and usher in new possibilities for more effective, inclusive, and sustainable approaches. These results support my social hypothesis that (H_3) the level of cooperation and coordination of lethal management methods negatively correlates with WTD density due to increased regional management efficacy.

4.5.4. Limitations—While useful in examining complex systems, theoretical models require a consideration of their inherent constraints. It is imperative to acknowledge these limitations to effectively interpret the results and understand their applicability (Helfat 2007, Raik et al. 2008, Conte et al. 2014). While agent-based models can offer qualitative and sometimes quantitative insights, their main purpose is to explore and understand dynamics of complex systems rather than to make precise predictions (Railsback et al. 2006, Railsback and Grimm 2019). I created these models, in the context of this study, not as conclusive assessments but as instruments to stimulate consideration and conversation (Wilensky and Rand 2015, Railsback and Grimm 2019). As with any models, this abstracted model comes with limitations related to logistics, data, and theory.

Like all studies, logistic constraints (e.g., funding, time, effort, experience, and practicality) influenced the course of this research, but I designed the model to robustly address the research questions within the margins of these limitations, ultimately rendering a distinct and novel study. I mitigated data-related challenges (e.g., sourcing and gaps) by cautiously selecting reliable data sources (e.g., prioritizing rigorous study designs and proximity to study area) and diligently filling data gaps (e.g., accessing non-open-source/gray literature, consulting experts). Theory constraints were a product of the scope (limited to New England), assumptions (e.g., all hunters act the same), simplifications (e.g., deer cannot immigrate or emigrate the landscape), and methodologies (e.g., parameterizing with focal town averages) of the model. I employed mitigation strategies such as a mixed-methods approach, defining model success criteria *a priori,* and leveraging pattern-oriented modeling to align phenomena of interest with real system patterns (Railsback and Grimm 2019, Strijker et al. 2020). Ultimately, the oversimplification and removal of inherent complexity enabled the assessment of this system's theoretical underpinnings.

4.5.5. Significance and Implications—This study contributes to the growing discourse of WTD management coordination dynamics, enriching the theoretical framework of this system in New England. These discoveries collectively yield insights for local and regional deer management and conservation efforts within the region. Through the exploration of challenges related to coordinating WTD management efforts across scales and contexts, this study emphasizes the importance of considering the multifaceted social and ecological repercussions of institutionally disjointed and spatially fragmented management systems. By leveraging a science-based, interdisciplinary framework, the findings of this research have the potential to inform coordination and guide more effective and sustainable WTD management practices in the region.

In a broader context, these results resonate with the overarching challenge of wildlife management in human-dominated landscapes (Piccolo et al. 2000, Siemer et al. 2004, Smith 2009). Beyond offering insights to New England communities, these findings hold implications for the wider realm of wildlife conservation and human-wildlife coexistence in coupled natural-human systems. Collectively, they provide insights into wildlife management coordination and its influence on achieving societal and ecological objectives. In alignment with existing literature, coordinated endeavors are frequently essential in addressing human-wildlife conflicts across municipal boundaries (Valdez et al. 2006, Pérez-Espona et al. 2009, Boulanger et al. 2014, Fattorini et al. 2020). Evaluating coordination through agent-based model development can serve as a blueprint for addressing similar challenges with other wildlife species in different contexts, promoting overall human-wildlife coexistence (Alt et al. 1992, Feit 1998, Feng et al. 2021). These findings ultimately underscore the importance of science-based, adaptive management approaches in tackling dynamic wildlife population issues within a changing world.

4.5.6. Suggestions for Future Research—Future research in this domain can strengthen the theoretical foundations of management coordination by investigating broader spatiotemporal scales and contexts, exploring stakeholder and wildlife dynamics to improve model reliability, and by assessing alternate applications of this study's framework to mitigate human-wildlife conflict in other regions.

Future research in the realm of WTD management coordination can encompass a broader geographic scope to facilitate the generalization of findings across diverse ecological and sociocultural contexts. By conducting studies in different regions, researchers can assess how coordination strategies can be adapted and applied to achieve effective WTD management on a larger scale, taking into account regional variations. Similarity, temporal dynamics represent another avenue for investigation, offering insights into how coordination evolves over time and its effects on WTD population dynamics. This temporal perspective can provide a more in-depth understanding of the system's behavior, highlighting the challenges and opportunities for maintaining effective coordination over extended periods (Callahan 1984, Franklin 1989, Mirtl and Krauze 2007, Lindenmayer et al. 2012, Dinca et al. 2018). Comparative studies, focusing on regions with varying levels of coordination in their WTD management systems, are an important aspect to consider. Such studies can identify best practices, challenges, and factors that influence the effectiveness of coordination efforts, thereby offering guidance for developing successful coordination strategies that can be applied across different regions and contexts.

To advance our understanding of wildlife management coordination, future studies can fine-tune agent behavior of the model in this chapter, capturing the complexities of human decision-making and wildlife responses more realistically. A more accurate representation of these behaviors will provide insights into how coordination can be optimized, enabling better-informed management strategies that align with both ecological and social objectives. Research can consider the integration of stakeholder preferences into the analysis, examining how community attitudes and interests affect the success of coordination efforts. Understanding stakeholder dynamics can lead to the development of strategies that better align with community preferences, fostering greater levels of social acceptance systems (Messmer et al. 1997, Chase et al. 2000, Leong et al. 2009, Davies and White 2012). Moreover, researchers can explore the feasibility and impact of other management methods such as non-lethal fertility control in an agent-based model setting. Investigating how coordination can support and integrate alternate approaches may broaden the toolkit for managing WTD populations, potentially offering insights into new opportunities that arise from increased cooperation.

Researchers can also explore the outcomes of integrating adaptive management approaches, particularly in dynamically changing environments such as the human-deer New England landscape. Understanding how adaptive strategies interact with coordination efforts is important for achieving long-term success in addressing wildlife challenges. The integration of adaptive management principles into coordination efforts may enhance adaptability to unforeseen circumstances, leading to more resilient and effective programs. Additionally, future research can delve into broader human-wildlife coexistence issues, exploring how coordination in WTD management can inform coexistence strategies for other wildlife species in diverse human-dominated landscapes (Franklin 1989, Mirtl and Krauze 2007). The lessons of this study can serve as a model for addressing broader challenges of human-wildlife coexistence, emphasizing the transferability of the methodologies and insights of this project.

4.6. Conclusion

This research aimed to investigate the dynamics of WTD management coordination in New England across 3 spatial scales. Through agent-based model simulations, I assessed the theoretical effectiveness of different management strategies, explored the impact of scales in influencing management outcomes, and examined the role of cooperation and coordination in shaping local and regional WTD densities. This study evaluated the complexities within this system, exemplifying the tradeoff between accommodating diverse stakeholder views and implementing regional deer population control. While communities may find common ground in management preferences at smaller scales, this consensus may not translate to regional scales due to varying conditions and priorities.

The findings consistently supported the notion that coordination of WTD management efforts can be highly important. Within individual towns (assessed with scale 1), the combination of sharpshooting and hunting was the most effective strategy for reducing local WTD density. This aligns with previous studies, underlining the efficacy of these methods when employed in conjunction. When examining coordination among neighboring towns (scales 2 and 3), I identified a clear trend: increased coordination consistently led to reduced WTD densities inside and outside the towns conducting said management. Notably, the model indicated that achieving significant reductions from the initial population levels required 100% management coordination based on current New England contexts, emphasizing the need for holistic, large-scale efforts in achieving social and ecological deer management goals in the region.

This research contributes to the field of WTD management and wildlife conservation as a whole. It advances the theoretical foundations of WTD management in New England, confirming the importance of cooperation and coordination in WTD population control. Furthermore, the findings offer practical insights for wildlife management in human-dominated landscapes, highlighting the potential of coordination and the combination of complementary strategies as a model for addressing similar challenges with other wildlife species. Ultimately, this study underscores the need for flexible and evidence-driven management approaches to tackle evolving challenges in wildlife population management within an ever-changing global environment. However, it is important to acknowledge the limitations of this research when applying results to various contexts, such as logistic constraints, data-related challenges, theoretical simplifications, and model assumptions.

Building on this study, future research avenues include the exploration of diverse spatiotemporal contexts, the improvement of models through the examination of stakeholder preferences, the consideration of alternatives and adaptive management, and the application of findings and methodologies to broader human-wildlife coexistence challenges. In conclusion, this research provides insights into WTD management coordination dynamics, emphasizing the importance of collaboration, and offering practical implications for wildlife management based on theory. By conclusively addressing the original research questions, this study contributes to the fields of wildlife management and ecological theory, setting the stage for a more sustainable future between human communities and resident wildlife.

5. CONCLUSION

The central research problem that underpins this study revolves around the multifaceted challenge of managing white-tailed deer (*Odocoileus virginianus*, henceforth “WTD” or “deer”) populations in New England amid rapidly changing social and ecological landscapes. This problem encompasses several interconnected factors that collectively defined the complex nature of WTD management in the region. These factors include the ecological consequences of overabundant WTD populations, the social intricacies involving diverse stakeholder groups, and the theoretical underpinnings of coordination among municipalities. The research problem extends beyond New England, reflecting broader challenges in wildlife management, human-wildlife conflicts, and ecosystem imbalances faced by regions worldwide. To address this complex issue, I started by asking:

> *How can New England WTD populations be effectively managed in the face of evolving ecological dynamics, shifting stakeholder interests, and the complexities of coordination among municipalities?*

Thus, my project aim was to investigate strategies for the effective management of New England WTD populations in light of changing ecological dynamics, fluctuating stakeholder interests, and the impact of municipal coordination. The overarching purpose of this dissertation research was to gain multifaceted insights into the ecological, social, and theoretical dimensions of WTD management in New England. While promoting informed, science-based, and sustainable wildlife management approaches, the research objectives were to address current WTD management challenges through 3 chapters that ultimately revealed:

- *Ecological Insights*: Through this facet, I sought to assess the ecological challenges posed by overabundant WTD populations, investigate the influence of various WTD management approaches on WTD population density, and identify thresholds of management parameters that effectively reduce local WTD populations.
- *Social Insights*: In this dimension, I aimed to explore the diverse interests and perspectives of stakeholders involved in New England WTD management, assess the social acceptability of different management strategies among various stakeholder groups, and investigate the role of stakeholder engagement in shaping WTD management decisions.
- *Theoretical Insights*: With this aspect, I delved into the theoretical underpinnings of WTD management systems, examining the impact of coordination among municipalities on management dynamics, assessing the effectiveness of different management strategies and their spatial implications, and investigating the spatial scale at which coordination becomes crucial for successful WTD management efforts across diverse contexts.

The broad goal of this research was to provide a holistic understanding of WTD management dynamics within the context of evolving natural-human systems in New England. The interconnected nature of the aims and objectives demonstrated the complexity of the greater problem addressed by this research and its potential significance for the sustainability and health of coupled natural-human systems worldwide.

5.1. Approach

In this study, my research methodology was aimed at investigating the intricate dynamics of the WTD management system in New England. To achieve this, I adopted a mixed-methods research style, combining qualitative and quantitative approaches to gain multifaceted insights and strengthen reliability of conclusions. The methodology involved various data collection techniques, including field data collection, case study analyses, computer simulation modeling, and social science surveys.

One of the central pillars of this study's methodology was the development of agent-based models, which allowed for the exploration of WTD management dynamics across spatial scales, temporal ranges, and distinct contexts. I parameterized and interpreted the models using estimates and surveys from state wildlife agencies, ecological field data, social science insights, expert opinion, and existing literature. By integrating ecological and social science dimensions, I aimed to provide a unique perspective of the research problem at hand.

During the data collection and analysis phase, I encountered several limitations and challenges that I meticulously mitigated through a variety of techniques. Funding, time, practicality, and other logistic constraints defined the path of this study but ultimately manifested a unique research project. Noting that the primary purpose of the models was to explore and understand dynamics rather than provide precise predictions, I acknowledged, mitigated, and dismissed a variety of data, model, and theoretical constraints given the study questions. For example, though unrealistic, assigning uniform behavior to all deer facilitated the pursuit of knowledge and enabled the investigation of this complex system in light of the research questions. Mitigation strategies included: defining success criteria a priori, filling knowledge gaps with expert opinion and the literature, employing a mixed methods approach, integrating diverse data sources, using pattern-oriented modeling, and explaining assumptions of limitations in the discussions.

5.2. Findings

To better understand dynamics and identify effective WTD management strategies in New England, this research encompasses 3 distinct chapters that collectively contributed to the development of unique insights. After the introduction, Chapter 2 explores the interplay between hunters, hunting land access, and local deer density in 11 focal towns. Chapter 3 extends this investigation to assess the feasibility of sharpshooting in maintaining WTD populations across a range of contexts. Chapter 4 widens this lens to assess the role of WTD management coordination at various scales. Together, these chapters paint an integrated picture of the complexities and opportunities inherent in managing WTD populations in New England.

In Chapter 2, I explore how factors like land access and hunter density interact to influence local WTD populations in New England towns. The results reveal specific hunting land access thresholds required to trigger a decline in WTD populations for various hunter density scenarios. For example, in Carlisle, MA, the model estimates that the existing hunter density and land access can control the local WTD population, but with low hunter density (half the current estimate), 17.8% hunting access of the town may be necessary to achieve similar effects. Conversely, high hunter density (double the current estimate) may require 9.0% access. Overall, the models estimates that 9 of 11 towns can effectively maintain their local deer populations with current estimates. However, with anticipated hunter declines (illustrated here as half the current estimate), between 48.9% and 74.8% of town lands may need to be open to hunting designation to achieve similar deer population effects.

Chapter 3 extends the analysis to assess the necessity of sharpshooting in maintaining local WTD populations in different situations. The findings indicate that most focal towns can effectively sustain their WTD populations at zero growth using the currently estimated management models, eliminating the need for sharpshooting. However, the results underscore the potential role of sharpshooting when reductions in hunter density and hunting access occur. In such scenarios, sharpshooting may become a necessary strategy to regulate local deer populations in the face of a declining hunter population and diminishing land access. Importantly, the results indicate that stakeholders play a central role in determining the success of sharpshooting efforts, making their education, engagement, and acceptance top priorities. This chapter sheds light on the nuanced dynamics of the potential role of sharpshooting in New England urban WTD management, emphasizing its relevance in specific contexts where hunting may not be sufficient.

Chapter 4 explores the broader theme of WTD management coordination in New England, spanning 3 spatial scales to evaluate the impacts of stakeholder cooperation. The results consistently highlight the importance of coordination, both within a single town (scale 1) and across multiple municipalities (scales 2 and 3). Effective coordination between neighboring towns consistently led to lower WTD densities inside and outside of the management areas, demonstrating the role of larger scale collaborative efforts in managing WTD populations across space and time. Furthermore, this chapter emphasizes the need for adaptive strategies that consider the unique circumstances of each town or municipality. When aligned with community interests, the findings showcase the potential for significant reductions in WTD densities when towns coordinated their management efforts effectively, offering a path forward for more successful WTD population management in New England and similar regions.

5.3. Interpretation

The central research question guiding this study was: "How can New England WTD populations be effectively managed in the face of evolving ecological dynamics, shifting stakeholder interests, and the complexities of coordination among municipalities?" Throughout this investigation, I systematically explored the intricate aspects of New England WTD management, considering these relevant driving factors through 3 core objectives and 3 chapters.

Objective 1 aimed to unravel the ecological intricacies of managing WTD populations in New England. This involved conducting a literature review and evaluating surveys to accurately parameterize an ecological agent-based model depicting a coupled natural-human system (Objective 1a). These models ultimately generated insights regarding the connections between the ecological and social dimensions of this system, such as how stakeholder perceptions indirectly influence WTD population size and resulting ecological impacts (Chapters 2-3). Additionally, I assessed how various WTD management approaches influence the density of WTD populations within a given area by leveraging the power of ecological agent-based modeling (Objective 1b). The research highlighted that different management strategies can exert varying degrees of influence on WTD population density, as exemplified by the simulation models in Chapters 2-4. For example, results in chapter 3 indicated that sharpshooting and hunting combined have the greatest WTD population reduction effect in this context. Furthermore, I identified specific thresholds of management parameters that successfully reduced local WTD populations through ecological modeling and analyses of empirical data (Objective 1c). For instance, in Chapter 4, the analysis estimated that 100% management coordination of both sharpshooting and hunting is required across scale 3 (13 total towns, each 5.7 km^2) to effectively reduce the collective WTD density in this context.

Objective 2 explored the social dimensions of WTD management in New England. This encompassed understanding the interests and perspectives of stakeholders involved in WTD management through a stakeholder analysis that combined surveys, interviews, and expert opinion (Objective 2a). The research findings uncovered the complex array of stakeholder interests, as exemplified by the stakeholder mapping in Chapter 3, illustrating the diverse stakeholder groups and their varying levels of power and interest. Furthermore, I assessed the social acceptability of various WTD management strategies by conducting surveys and analyzing public opinion (Objective 2b). In Chapter 3, for example, results demonstrated the polarizing nature of sharpshooting in certain contexts, highlighting the intricate nature of this paradigm and the importance of tailoring management to individual community preferences. I also investigated the pivotal role of stakeholder engagement in shaping WTD management decisions through case study and literature analyses (Objective 2c). Chapter 3 showcased how stakeholder engagement influenced decision-making, where collaborative efforts between wildlife agencies, hunters, and residents shaped the success of management strategies.

Addressing Objective 3 involved understanding the theoretical underpinnings of WTD management in New England. I began by examining the influence of coordination among municipalities on WTD management dynamics through agent-based modeling that simulated different coordination scenarios (Objective 3a). The findings emphasized the importance of regional collaboration in achieving successful WTD management outcomes, as illustrated in Chapter 4 through simulations of coordinated and non-coordinated management efforts. Additionally, I assessed the effectiveness of different management strategies and their spatial implications through spatial analysis and modeling (Objective 3b). In Chapter 4, spatial analysis demonstrated how the combination of hunting and sharpshooting at scale 3 consistently led to lower deer densities, substantiating the effectiveness of certain strategies and their spatial implications. Lastly, I investigated the spatial scale at which coordination becomes crucial for successful WTD management efforts by analyzing data on coordination patterns and ecological dynamics (Objective 3c). Chapter 4 showed that coordination was crucial at both local and regional scales, demonstrating that uncoordinated towns without management acted as *de facto* refuges for deer and facilitated their population growth.

The findings of this study largely aligned with existing theories and practices in wildlife management. The importance of considering both ecological factors (Palmer et al. 1983, Callahan 1984, Lindenmayer et al. 2012) and stakeholder interests (Messmer et al. 1997, Raik et al. 2005, Leong et al. 2009, Davies and White 2012) echoed the principles of adaptive management, which emphasizes flexibility and collaboration (Berkes et al. 2000, McCarthy and Possingham 2007, Kaji et al. 2010). However, this study also challenged the assumption that a single management approach fits all situations, highlighting the need for tailored strategies based on local conditions (Harrison et al. 2012). Furthermore, the findings regarding the positive impact of coordination among municipalities aligned with theories of collective action and shared resource management (Casebeer 1978, Alt et al. 1992, Feit 1998, Feng et al. 2021). Collectively, the results emphasized the potential benefits of inclusive, regional approaches to wildlife management.

The significance and implications of the collective chapters contribute to the scientific field by offering unique insights into the sustainability of the current New England WTD management system. In Chapter 2, the research explored the challenges posed by reduced hunter recruitment and limited land access. These findings underscored the significance of proactively addressing these issues to maintain effective deer population management. By recognizing the potential consequences of declining hunter numbers and land access limitations, we gain insight into the importance of engaging with the hunting community and private landowners to increase opportunities for hunting. Chapter 3's exploration of sharpshooting as a WTD management strategy revealed its potential role in addressing overabundant deer populations while considering social acceptability. This contributed to the existing body of knowledge by offering science-based conclusions of an alternative management approach and emphasizing the need to assess public attitudes toward such strategies. The result that sharpshooting's effectiveness is contingent upon community support highlights the importance of stakeholder engagement in shaping management decisions. Chapter 4 investigated the spatial implications of WTD management coordination among municipalities in New England. The finding that 100% coordination is required with both hunting and sharpshooting to effectively maintain local WTD populations in this context emphasized the critical role of regional cooperation. Similarly, the result that just a few uncoordinated towns (lacking management) can become *de facto* refuges for deer to reproduce and grow underscored the potential effects of incomplete coordination. Overall, these insights highlighted the need for regional cooperation, stakeholder engagement, and adaptive management strategies to maintain balanced WTD populations.

5.4. Future Research

Future research can draw upon the foundations laid by this study to build a multifaceted understanding of WTD management in New England. Researchers can integrate and expand upon the findings of this research to address the identified knowledge gaps and contribute to a more informed perspective of this complex system. For example, future studies exploring long-term ecological effects can use the ecological modeling framework developed here to simulate the impacts of various management scenarios over longer periods (Callahan 1984, Franklin 1989, Bonabeau 2002, Urban 2005, Lindenmayer et al. 2012). This approach could provide insights into how ecosystems evolve and adapt in response to changes in deer populations and management strategies. Moreover, researchers can take advantage of the stakeholder engagement insights gained from this study to design and test innovative approaches for fostering collaboration among diverse stakeholder groups (West and Parkhurst 1973, Stout and Knuth 1995, Leong et al. 2009, Smith 2009, Davies and White 2012). By refining and tailoring engagement strategies, future research can contribute to more inclusive and effective decision-making processes in deer management (Palmer et al. 1983, Chase et al. 2000, Raik et al. 2005).

Spatial dynamics of deer populations and management strategies offer another avenue for building upon this research. Researchers can expand the spatial modeling efforts initiated in this study to investigate the broader landscape-scale factors influencing deer populations (Turner et al. 1993, Sterman 2001, Shi et al. 2006, Heppenstall and Crooks 2012, DeAngelis and Yurek 2016). Detailed studies on deer movement patterns, habitat preferences, and landscape connectivity can provide a deeper understanding of how deer interact with their environment (Piccolo et al. 2000, Scott C. Williams et al. 2008, Williams 2008). Additionally, future research can explore how climate change and land use alterations impact deer populations at regional scales, allowing for a more holistic assessment of the ecological dynamics (Railsback et al. 2006, Tang and Bennett 2010, Gilbertson et al. 2022).

Ethical considerations in WTD management also represent an area open for further exploration. Future research can investigate the ethical dimensions of specific management strategies and assess how they align with societal values and acceptance (Frank et al. 1993, Warren 2000, Siemer et al. 2004, Smith 2009, Figura 2017*a*). By conducting in-depth ethical analyses, researchers can provide insights into the ethical complexities surrounding deer management practices (Leopold 1933, Messmer et al. 1997, Kelly 2018). Comparative studies with other regions or countries can also shed light on how different cultural and societal contexts influence the ethics of deer management (West and Parkhurst 1973, Stollkleemann and Welp 2006, Leong et al. 2009, Davies and White 2012).

Adaptive management strategies, as proposed in this study, similarly offer a promising framework for future research. For example, researchers can develop and test adaptive management approaches tailored to the New England context or other regions (Brinkman et al. 2007, Kaji et al. 2010, Levin et al. 2012). Case studies and field experiments can help refine these strategies and provide practical guidance on their implementation (Lindenmayer et al. 2012, Railsback and Grimm 2019, Strijker et al. 2020). Similarly, researchers can promote enhanced data integration and sharing by exploring innovative data-sharing platforms and protocols that facilitate collaboration among stakeholders and improve the accuracy of models (Sauer et al. 2005, Michener 2015). By focusing on adaptive management and developing better data-sharing procedures, future research can contribute to the development of flexible and science-based approaches to WTD management.

Lastly, research into the policy and human dimensions of WTD management holds potential to benefit the field. In-depth examinations of existing policies, their impact on deer management, and their alignment with management goals can provide novel insights (Pérez-Espona et al. 2009, Meek 2013, Droe 2021, Feng et al. 2021). For example, comparative policy analyses across different regions can offer a broader perspective on the effectiveness of policy frameworks (Thomas and Adams 1985, Wright and Fesenmaier 1988, Atkinson 1991, Nugent et al. 2011, Levin et al. 2012). Future studies can also investigate the cultural and societal perspectives on deer, hunting, and wildlife conservation (Raik et al. 2005, Smith 2009, Kelly 2018). By understanding the motivations, values, and beliefs of different communities, future research can offer a more holistic understanding of the social complexities influencing deer management outcomes (Chase et al. 2000).

5.5. Reflections

Reflecting on the research journey, my initial conceptualization of the research project was largely shaped by the identification of knowledge gaps by the larger research team. This project evolved over time, in part due to the challenges posed by the COVID-19 pandemic. Originally, I planned to conduct field research involving the collection of WTD SARS-CoV-2 samples for analysis and agent-based model parametrization, but pandemic-related restrictions altered the project's trajectory. As a result, I shifted my focus towards exploring management dynamics within the New England WTD population based on available datasets. This shift in scope ultimately led to a unique perspective that contributed to addressing knowledge gaps in the field of ecology. Addressing data gaps was another challenge, highlighting the importance of further research to inform future modeling endeavors.

My understanding of the research topic underwent a profound transformation as I delved deeper into the subject matter. I started with limited knowledge of the New England WTD management system but learned extensively about its complexities throughout the research process. A significant area of personal growth was in the social sciences, where I gained expertise in evaluating social-ecological systems. I also expanded my knowledge in reading and history, which enabled me to leverage historical texts to supplement current interpretations and anticipate future directions. Overall, I learned that these systems are highly intricate, with ecological, social, and theoretical dimensions that interact in unexpected ways. I learned that the interactions studied in this dissertation shed new light on the complexity of these systems, emphasizing the need for tailored approaches to address different contexts and shifting situations.

Unexpected findings and insights emerged during the research, with 1 result particularly surprising to me. I was struck by the significant role of stakeholder acceptance in wildlife management. Unlike historic approaches where management was often absent or enforced through top-down mechanisms, modern WTD management heavily depends on stakeholder perspectives and engagement. This realization prompted me to conduct more in-depth stakeholder analyses to better understand their influence in this paradigm and how they shape management outcomes.

In terms of ethical considerations, a key factor was the need to include diverse stakeholder opinions and perspectives throughout this research. Ensuring inclusivity was crucial to reduce biases and produce reliable conclusions relevant to the communities under study. Additionally, maintaining research integrity was essential for me in contributing dependable insights to the field. I prioritized data quality, transparency, accurate recording of results, and rigorous reporting throughout all research phases to ensure the reliability of my recommendations and their usefulness in real-world management scenarios.

In closing, this research has illuminated the multifaceted nature of WTD management in New England and its broader implications for wildlife management and conservation. The findings presented here emphasized the critical importance of adaptive strategies, regional cooperation, and stakeholder engagement in implementing effective and sustainable deer management approaches. This study underscored that wildlife management is not solely an ecological endeavor but a complex interplay of ecological, social, and theoretical factors. The significance of this research extends beyond New England, offering insights and methodologies that can inform wildlife management practices across diverse contexts. By embracing the inclusive, science-based approaches outlined in this research, wildlife managers can pave the way for a new era of collaborative and sustainable deer management practices that resonate with communities and ecosystems alike. Ultimately, the quest to sustainably manage WTD populations serves as a microcosm of the broader challenges facing wildlife conservation in a changing world. As we navigate the complex dynamics of wildlife management, we must ask ourselves: Are we prepared to adapt, collaborate, and innovate to promote a harmonious coexistence between humans and wildlife?

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APPENDIX A. CHAPTER 2 MODEL DESCRIPTION.

Purpose and Patterns

Purpose

The aim of this model was to explore how varying levels of hunting access and hunter density influence a municipality's ability to effectively manage white-tailed deer (*Odocoileus virginianus*, henceforth "WTD" or "deer") in New England. In this region, the typical objective of WTD management is to decrease deer populations to alleviate the adverse consequences of deer overabundance (NYSDEC 2007, NDTC 2008). I investigated dynamics of variable hunting access and hunter density levels through an agent-based model analysis of 11 New England focal towns (Table 22). In reality and reflected in the models, 3 of the towns implemented sharpshooting and 9 employed hunting. The broad goal of this model was to analyze the impacts of different amounts of open access and hunter densities on the ecological, social, and theoretical dimensions of the New England WTD management system.

Patterns

To assess the model's efficacy, my primary focus was on its capacity to simulate realistic fluctuations in hunter, sharpshooter, and WTD population dynamics under varying levels of hunting land access and hunter density. Additionally, during the validation phase, I analyzed a range of relevant phenomena through pattern-oriented modeling to promote model reliability in depicted the actual system in context of the research questions.

Entities, State Variables, and Scales

Entities

The entities in this model consisted of the observer (determines changing global variables), agents (WTD, hunters, sharpshooters), grid cells (virtual geographic locations), and the global WTD management landscape (population dynamics, coordination levels).

State Variables

The observer controlled global state variables such as year, month, and week. Static observer variables were considered parameters and are defined in the associated submodels. Cells (patches) were the lowest level habitat entity depicting estimated urban zones, huntable areas (Goethlich 2023), and land cover types (forest, grassland, water, wetland); variation within cells was not represented. Each cell represented a 2-dimensional horizontal plane, and because their characterization did not change throughout the model, their classifications were treated as state variables instead of parameters. Hunters and sharpshooters did not have any state variables, and WTD could be males or females, and fawns (age < 1 year), yearlings (1 year < age < 2 years), or adults (age > 2 years).

Scales

To portray dynamics at a meaningful level, this model employed continuous weekly time steps starting in January, covering a temporal span of 10 years to illustrate patterns unfolding over a decade. To maintain an agent-based perspective while adhering to practical timeline limitations, this 2-dimensional discrete spatial scale represented real New England towns from approximately 12.3 mi^2 (31.9 km^2) to 49.9 mi^2 (129.2km^2), with pixels of 900 m^2 (30 x 30 m). These fine-scale, bounded landscapes prevented agents from exiting the model's environment, thereby constraining dynamics relevant to the research focus (e.g., population dynamics) while excluding factors like immigration and emigration.

Process, Overview, and Scheduling

Process

The model focused on essential processes involving WTD ecology and behavior, hunter and sharpshooter dynamics, and the varying degrees of hunting land access and hunter density. Notably, the model deliberately excluded processes that were not directly related to the research question to produce practical and pertinent results. For example, weather conditions such as harsh winters or drought years were not explicitly incorporated into the model but were indirectly accounted for through an average non-harvest mortality rate. Likewise, the model maintained a closed population framework, omitting agent immigration and emigration, as the primary objective was to investigate fundamental mechanisms relevant to the research question without introducing unnecessary complexities.

Overview

During *setup*, grid cells adjusted their state variables based on the defined interface selections, which included the town, viewable GIS layers, and relevant agent parameters (e.g., initial deer population, hunting access, etc.). Agents continuously updated their state variables on a weekly basis throughout the entire 10-year simulation, adhering to specific timeframes allocated for each process. For example, submodels like *birth* and *yearling dispersal* were confined to May, while the *rut* was exclusively scheduled for November. Conversely, processes such as WTD aging, movement, and non-hunting mortality occurred during every time step.

Scheduling

The model initiated at the start of the calendar year in January. First, it executed the *setup* process to configure the landscape in accordance with the interface parameters. This *setup* procedure involved clearing the interface from previous runs, establishing initial parameters, creating landscapes and agents as defined by the selection of specifications, and introducing WTD group dynamics to form realistic group structures. In addition to carrying the model forward each week, the *go* procedure was responsible for halting the model under 2 conditions: when there were no deer remaining or when a period of 10 years had elapsed. Additionally, this procedure governed the movements and interactions of agents throughout the landscape. Following each tick (i.e., time step), the model generated outputs on the interface for the user to monitor the desired parameters. The following describes the *setup* and *go* procedures:

- SETUP:
    - Clear all information from previous runs and reset time
    - Create landscape
        - Depict layers according to town selection
        - Apply land access (for hunters and sharpshooters, when applicable)
        - Calculate habitat suitability index (HSI) for deer
    - Create and place agents on model landscape (e.g., WTD, hunters, sharpshooters)
        - Form deer social groups based on coded WTD group dynamics
- GO:
    - Track time (week, month, year, season) each tick
    - Age deer by 1 week each tick
    - Non-harvest mortality based on predetermined sex and age class rates each tick

        - Review groups and select new group leaders if one dies
    - Move deer in home range according to sex, season, and HSI
    - Form bachelor groups after the rut in January
    - Disperse yearlings in May
        - New home range selection based on other group locations
    - Breakdown female groups in May to prepare for fawns
    - Birth new fawns in May according to birth rates
    - New female group formation in October
    - Bachelor group breakdown in preparation for the rut in early November
    - Rut occurs in November
    - Each tick, move hunters/sharpshooters within designated areas, when applicable
    - Hunting mortality from October through December based on access and sex-/age-specific mortality rates, when applicable
    - Sharpshooting mortality occurs in urban zones from January through March, when applicable
    - Outputs are generated at the end of each time step unless otherwise specified
    - Time advances by 1 week

Design Concepts

At the system level, this model addressed a pressing issue in modern WTD management: Are there enough hunters and open access areas to effectively manage local WTD populations in New England? By exploring the social, ecological, and theoretical foundations of this historic management paradigm, the model sought to answer this research question and provide unique insights into the sustainability of hunting in the region. While existing literature has tackled this issue, this model offered a unique approach by combining agent-based model analysis with real-world case study data.

Basic Principles

This model operated on both agent and system levels, integrating ecological theory to govern individual WTD behaviors (e.g., dispersal distance, home range size) and the emergent ecological patterns of WTD populations (e.g., mortality rate, population growth). Additionally, it utilized social and political theory at both the agent and system levels to determine the movement and success of hunters, drawing from open access theory (e.g., the availability of hunting land). By combining these theoretical concepts, the model's output contributed to our understanding of natural resource management theory, particularly in the context of WTD sharpshooting feasibility in New England.

Emergence

Some of the key model results that emerged from adaptive decisions and behaviors of agents were: WTD population size, density, and spatial pattern; and hunter and sharpshooter success rates and spatial distributions. These patterns emerged from interactions of hunters, sharpshooters, and management land access, ultimately influencing the dynamics of WTD. Directly related to the research question, these outputs correlated to the efficacy of sharpshooting under diverse social and ecological contexts. Other forms of emergence not directly related to the research question were useful in the validation process, such as WTD sex ratio, age structure, and seasonal behavior.

Adaptation

WTD navigated the landscape based on their HSI which determined how suitable a certain patch was for on a scale from 0.00 to 1.00. For example, high-intensity development areas (e.g., industrial) were assumed completely unsuitable (0.00), open areas were moderately suitable (0.47), and forest was considered highly suitable (0.63) (Flemming et al. 2004). Within each deer's home range, they chose patches with higher HSIs via direct objective-seeking, though there was a programmed element of randomness in these choices (see *Stochasticity* below). The decision to select a new patch was driven by time (they moved every week) or dispersal. When yearling WTD dispersed in May, they selected their new home range through direct objective seeking based on the location of other groups. They sought to join groups of their same sex (female or bachelor groups) if they had under 20 deer but looked for a new group if there were 20 or more deer (considered group carrying capacity) (Xie et al. 1999, Van Buskirk et al. 2021). Hunters and sharpshooters displayed adaptive behavior through indirect objective seeking by harvesting deer in response to harvest probabilities when deer came within 0.5 mi of hunters or 0.2 mi of sharpshooters during their respective seasons.

Objectives

The objectives of WTD were linked to increasing their fitness, which encompassed their survival and reproductive success. Conversely, hunters and sharpshooters aimed to harvest deer, serving as a population control measure. The rationale behind these objectives was straightforward: WTD naturally strive to survive, while in systems with lethal management, the goal is to harvest deer to manage population levels effectively. Each week during their seasons, hunters and sharpshooters moved within the landscape, and by chance, they came into proximity with a deer that could possibly be harvested. Their movement patterns and responses to cues drove their actions. When yearling WTD dispersed, their objective was to seek a new home range at a particular distance from their natal range. This decision-making process was influenced by their age and sex (Gilbertson et al. 2022). Yearlings sought groups of deer to join, driven by anti-predator instincts and reproductive considerations (Stanke et al. 2018). Consequently, the dispersal distances of deer were influenced by deer density and environmental factors (Piccolo et al. 2000, Fischer et al. 2015). In urban areas and regions with higher deer densities, deer tended to travel greater distances during dispersal (Piccolo et al. 2000, Gilbertson et al. 2022). Although this behavior was assumed to increase individual deer fitness, the model did not explicitly track fitness as an output measure.

Learning

Agents did not encompass mechanisms of learning in this model.

Prediction

WTD generally moved to patches with higher HSI values, implying their prediction of increased fitness. Similarly, yearling WTD used implicit prediction in their patch selection during dispersal, moving towards groups of other deer with the implied expectation of increasing chances of reproduction and reducing the likelihood of predation (Williams et al. 2008).

Sensing

All agents were assumed to have known (sensed) the time of year on a weekly time step, which governed WTD ecology and the presence of hunters and sharpshooters. WTD could also sense the direction they needed to travel to reach higher HSI patches and more suitable areas during dispersal, which was important in representing realistic WTD behavior.

Interaction

WTD directly interacted with each other during the rut, with these interactions determining female pregnancies. Meanwhile, hunters and sharpshooters directly interacted with WTD through harvesting and indirectly interacted by influenced their movement and spatial behaviors. Hunters and sharpshooters could only harvest WTD when they were within areas designated for hunting or sharpshooting; the model did not include poaching or harvest outside legally accessible areas.

Stochasticity

To introduce a realistic element of randomness into the model, various processes were implemented with a degree of stochasticity. During setup, agents were randomly distributed across the landscape in the areas where they could be present (e.g., hunters in open access areas, sharpshooters in urban zones, and deer anywhere). WTD distribution and movement included stochasticity as they chose a high HSI-valued patch in their home range with 30% randomness to represent incorrect decisions, obstacles, interference, or other realistic processes that could interfere with a WTD moving to the most suitable area. Other agent movements also incorporated stochasticity as they selected a new patch each week from their designated areas. All mortalities, whether from natural causes or harvest, were determined using probability distributions based on age and sex. For example, when a deer came within proximity of a hunter, the likelihood of its harvest was higher if it was an adult male compared to a fawn.

Collectives

To represent realistic spatial patterns and social dynamics of WTD, collectives were explicitly portrayed as assemblages of WTD social groups. The group structure changed based on sex and season, with bachelor and female groups forming after the rut and disbanding in preparation for the next rut. Bachelor groups consisted of up to 6 males and included yearling males once they dispersed in May (Xie et al. 1999, Van Buskirk et al. 2021). Female groups encompassed all females and any of their fawns (up to 20 per group) until the yearlings dispersed in May (Xie et al. 1999, Van Buskirk et al. 2021). These group limits contributed to shaping the emergent spatial arrangement of WTD across the landscape.

Observation

I designed the model to explore how dynamics would change under varying levels of WTD sharpshooting implementation. As a result, the primary outcome of interest was town-scale deer density. The graphical output on the interface tracked summary statistics related to this outcome, along with other data used in the validation process.

Initialization

The model aimed to assess the effects of variable open access levels and hunter densities on system dynamics, specifically, a town's ability to manage their local WTD population under relevant paradigms. With this goal in mind, during initialization, the user creates the model landscape with the SETUP command. The first step in this process is to clear the interface from all previous model runs and reset any previously recorded information. Then the landscape is created for each town that corresponds to town and selections on the interface. Unless specified otherwise, realistic management, population, and land cover parameters are depicted. Agent parameters (densities, sex/age ratios, etc.) are assigned based on predetermined values calculated for each focal town. Hunters and sharpshooters are initialized in their designates areas (hunters in hunting areas, sharpshooters in urban zones) and are initially hidden but show up later during their respective seasons. Hunters and sharpshooters start with no harvests/culls. WTD are dispersed semi-randomly in social groups within seasonal home ranges and according to their HSI. The model is initialized in the first week of January and runs for 10 years or until there are no deer left.

Input Data

The model does not use input data to represent time-varying processes.

Submodels

I designed the submodels to only include relevant processes to effectively address the research question and focus on the phenomena of interest. The submodels, their details, and their purposes are summarized below.

- SETUP
    - create-landscape: import GIS layers depicting town boundaries, land cover (forest, grassland, open water, wetland, low/medium/high development), estimated management land access areas (huntable areas for hunters and urban zones for sharpshooters), and HSI values for deer.
    - create-agents: create deer, hunters, and sharpshooters when applicable to the management selected, assign densities (all agents), home ranges (deer), social groups (deer) and age/sex distributions (deer), and distribute semi-randomly across landscape in their designated areas (sharpshooters in urban zones, hunters in open access areas, and deer anywhere). Key parameter values are depicted in Tables 22-23.
- GO

- update-time: advance time by 1 week each tick; track year, month (through get-month Julian calendar), week, and season; update parameters (e.g., seasonal home ranges for deer); and reset relevant parameters (e.g., annual hunter harvest) accordingly.
- deer-growth: age deer by 1 week each tick.
- non-harvest-mortality: each tick, deer die based on predetermined probability distributions of sex-, age-, and season-based non-harvest mortality rates (Tables 22-23). Deaths are tracked for each sex and age category, and if a group leader dies, a new eligible leader (based on age and sex) is randomly selected from that group (Verme 1977, Nelson and Mech 1986, Deelen et al. 1997, Xie et al. 1999, Williams 2008, Van Buskirk et al. 2021).
- move-deer: move each deer to a new random patch within their seasonal home range.
- form-bachelor-groups: in January, bachelor groups form with 1 randomly selected leader (of oldest males) after the rut in groups of 6 or less.
- yearling-dispersal: In May, yearlings disperse and select new home ranges based on proximity to conspecifics, prioritizing being in a group but not causing the group to exceed 20 deer (Tables 22-23) (Xie et al. 1999, Van Buskirk et al. 2021, Gilbertson et al. 2022)
- fawning: in May, bred female deer become pregnant based on pregnancy rates that result in model dynamics aligning with reality, and they change their behavior to solitary for their upcoming fawn birth.

- birth: in May, pregnant females birth 1 fawn; the fawn adopts its mother's home range and its sex is randomly assigned based on a predetermined age distribution (0.51: male, 0.49: female) (Verme 1983, Collier 2004).
- new-group-formation: in October, females form new groups with other females and their fawns (Xie et al. 1999, Williams 2008, Van Buskirk et al. 2021).
- mdisperse-before-rut: in November, males disperse before the rut and change their behavior to solitary as they search for a mate (Williams et al. 2008)
- rut: in November, when breeding-age males (> 1.5 years old) come within 3 patches of a female, the female changes her status to bred (Williams 2008).
- move-hunters: move each hunter to new random patch within their town's huntable areas.
- hunting-mortality: hunters harvest deer that are in huntable areas and within 0.5 miles (0.8 km, 27 patches) of their location based on a predetermined sex- and age-based harvest probability distribution (Tables 22-23) (Williams et al. 2008, Williams 2008, Norton 2015, NYSDEC (New York State Department of Environmental Conservation) 2019, MassWildlife 2020). Deer deaths and hunter harvest are tracked. When a hunter harvests 2 deer, they switch to hidden and do not harvest any more deer during that season.
- move-sharpshooters: move each sharpshooter to a new random patch within their town's urban zone.
- sharpshooting: sharpshooters harvest deer that are in urban zones and within 0.2 miles (0.3 km, 10 patches) of their location based on an unbiased predetermined

cull probability distribution (Tables 22-23; DeNicola and Williams 2008, Figura 2017*a*). Sharpshooter harvest is tracked, and they do not have a limit on their cull.

- track-output: to facilitate aligning the model with the real-world phenomena of interest through pattern-oriented-modeling, relevant outputs are tracked and displayed on the interface, such as key parameter values, population trackers, and sex/age distribution monitors (Wilensky and Rand 2015, Railsback and Grimm 2019, Grimm et al. 2020).

Table 22. Town-specific parameter breakdown for the agent-based models, depicting values, definitions, and sources. For clarity to US WTD managers, I adopted imperial units instead of metric (Kelly and Ray 2019).

Town	Pepperell	Lincoln	Carlisle	Weston	Sharon	Easton	Fenner	Manlius	DeWitt	Geddes	Clay
Town Area (mi^2)	23.2	15.0	15.5	17.3	24.2	29.2	31.1	49.9	33.9	12.3	48.9
Hunting Access (%)	20.65	6.03	10.18	11.31	18.00	25.79	63.85	33.22	0.00	0.00	21.00
Hunters (#)	581	222	170	251	416	101	188	183	126	0	155
Hunter Density (#/mi^2)	25.0	14.8	11.0	14.5	17.2	3.5	6.0	3.7	3.7	0.0	3.2
Sharpshooter Density (#/mi^2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.9	3.7	26.0	0.0
Initial Deer (#)	407	504	521	581	731	882	791	1269	862	313	1243
Deer Density (#/mi^2)	17.54	33.60	33.61	33.58	30.21	30.21	25.43	25.43	25.43	25.43	25.43
Harvest Mortality (%)	20	14	14	14	45	45	26	12	9	0	12
Antlerless Harvest Density (#/mi^2)	1.36	1.94	1.94	1.94	5.33	5.33	3.50	1.60	1.27	0.00	1.66
Buck Harvest Density (#/mi^2)	2.24	2.80	2.80	2.80	8.32	8.32	3.09	1.52	0.97	0.00	1.45

Parameter	**Definition**	**Source(s)**
Town Area (mi^2)	Areas calculated for each town in GIS.	GIS
Hunting Access (%)	The estimated percent open hunting access for each town, based on state and local setbacks and restrictions.	GIS
Hunters (#)	Hunter number estimate based on licenses sold in each town.	NYSDEC 2019, MassWildlife 2020
Hunter Density (#/mi^2)	Hunter density estimate based on licenses sold in each town.	NYSDEC 2019, MassWildlife 2020
Sharpshooter Density (#/mi^2)	The density of sharpshooters within the available culling areas.	Data from NYSDEC
Initial Deer (#)	Deer population estimates based on the most recent state wildlife population reconstruction methods.	NYSDEC 2019, MassWildlife 2020
Deer Density (#/mi^2)	Town-level deer density estimates based on population estimate and town area.	NYSDEC 2019, MassWildlife 2020
Harvest Mortality (%)	Deer harvest mortality according to population and harvest estimates.	NYSDEC 2019, MassWildlife 2020
Antlerless Harvest Density (#/mi^2)	Annual harvest density of antlerless deer (females and fawn males).	NYSDEC 2019, MassWildlife 2020
Buck Harvest Density (#/mi^2)	Annual harvest density of bucks.	NYSDEC 2019, MassWildlife 2020

Table 23. Agent-based model parameters, definitions, values, and sources. Values are averages of all focal towns in previous chapters. For clarity to US WTD managers, I adopted imperial units instead of metric (Kelly and Ray 2019).

Parameter	Description	Value	Source(s)
% Female Deer	Percent female deer relative to total deer in the population at time of data output (January 1).	58	Coe et al. 1980, Boulanger et al. 2012
% Male Deer	Percent male deer relative to total deer in the population at time of data output (January 1).	42	Coe et al. 1980, Boulanger et al. 2012
% Fawns	Percent fawn deer relative to total deer in the population at time of data output (January 1).	28.75	Collier 2004
% Yearlings	Percent yearling deer relative to total deer in the population at time of data output (January 1).	23.75	Collier 2004
% Adults	Percent adult deer relative to total deer in the population at time of data output (January 1).	47.5	Collier 2004
% Deer Population Growth	Realized deer population growth from annual spring births with hunting present.	30	Norton 2015, Van Deelen 2023
% Fawn Annual Non-Harvest Mortality	The annual non-harvest mortality percent for fawns relative to deer population.	69	Nelson and Mech 1986
% Yearling Annual Non-Harvest Mortality	The annual non-harvest mortality percent for yearlings relative to deer population.	22.5	Nelson and Mech 1986
% Adult Annual Non-Harvest Mortality	The annual non-harvest mortality percent for adults relative to deer population.	22.5	Nelson and Mech 1986
Fawn/Yearling Harvest %	Annual percentage of fawns and yearlings harvested by hunters relative to the total deer population.	10	Boulanger et al. 2012
Adult Harvest %	Annual percentage of adults harvested relative to the total deer population.	90	Boulanger et al. 2012
Buck Harvest %	Annual percentage of bucks harvested relative to the total deer population.	50	Boulanger et al. 2012
Sharpshooter Harvest Density (#/mi^2)	Annual density of deer culled by sharpshooters when implemented, based on most recent average of 3 towns.	11.8	Data from NYSDEC
Sharpshooter Density (#/mi^2)	Sharpshooter density when implemented in each focal town, based on most recent average of 3 towns.	3.88	Data from NYSDEC

Table 23 (*Continued*). Agent-based model parameters, definitions, values, and sources. Values are averages of all focal towns in previous chapters. For clarity to US WTD managers, I adopted imperial units instead of metric (Kelly and Ray 2019).

Parameter	Description	Value	Source(s)
Male Winter Home Range Radius (mi)	Winter home range for male deer.	2.77	Roden-Reynolds et al. 2022
Male Fall/Spring Home Range Radius (mi)	Fall and spring home range for male deer.	1.83	Roden-Reynolds et al. 2022
Male Summer Home Range Radius (mi)	Summer home range for male deer.	1.31	Roden-Reynolds et al. 2022
Female Winter Home Range Radius (mi)	Winter home range for female deer.	0.59	Roden-Reynolds et al. 2022
Female Fall/Spring Home Range Radius (mi)	Fall and spring home range for female deer.	1.2	Roden-Reynolds et al. 2022
Female Summer Home Range Radius (mi)	Summer home range for female deer.	0.67	Roden-Reynolds et al. 2022

APPENDIX A SOURCES

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APPENDIX B. CHAPTER 3 MODEL DESCRIPTION.

Purpose and Patterns

Purpose

The aim of this model was to investigate the feasibility of sharpshooting in managing white-tailed deer (*Odocoileus virginianus*, henceforth “WTD” or “deer”) populations in New England. In this region, the typical objective of WTD management is to decrease deer populations to alleviate the adverse consequences of deer overabundance. I investigated dynamics of sharpshooting through agent-based model analysis of 11 New England focal towns. The broad goal of this model was to analyze the impacts of sharpshooting on the ecological, social, and theoretical dimensions of the New England WTD management system.

Patterns

To assess the model's efficacy, my primary focus was on its capacity to simulate realistic fluctuations in hunter, sharpshooter, and WTD population dynamics under varying levels of sharpshooting. Additionally, during the validation phase, I analyzed a range of relevant phenomena through pattern-oriented modeling to promote model reliability in depicted the actual system in context of the research questions.

Entities, State Variables, and Scales

Entities

The entities in this model consisted of the observer (determines changing global variables), agents (WTD, hunters, sharpshooters), grid cells (virtual geographic locations), and the global WTD management landscape (population dynamics, coordination levels).

State Variables

The observer controlled global state variables such as year, month, and week. Static observer variables were considered parameters and are defined in the associated submodels. Cells (patches) were the lowest level habitat entity depicting estimated urban zones, huntable areas (Goethlich 2023), and land cover types (forest, grassland, water, wetland); variation within cells was not represented. Each cell represented a 2-dimensional horizontal plane, and because their characterization did not change throughout the model, their classifications were treated as state variables instead of parameters. Hunters and sharpshooters did not have any state variables, and WTD could be males or females, and fawns (age < 1 year), yearlings (1 year < age < 2 years), or adults (age > 2 years).

Scales

To portray dynamics at a meaningful level, this model employed continuous weekly time steps starting in January, covering a temporal span of 10 years to illustrate patterns unfolding over a decade. To maintain an agent-based perspective while adhering to practical timeline limitations, this 2-dimensional discrete spatial scale represented real New England towns from approximately 12.3 mi^2 (31.9 km^2) to 49.9 mi^2 (129.2km^2), with pixels of 900 m^2 (30 x 30 m). These fine-scale, bounded landscapes prevented agents from exiting the model's environment, thereby constraining dynamics relevant to the research focus (e.g., population dynamics) while excluding factors like immigration and emigration.

Process, Overview, and Scheduling

Process

The model focused on essential processes involving WTD ecology and behavior, hunter and sharpshooter dynamics, and the varying degrees of sharpshooting implementation. Notably, the model deliberately excluded processes that were not directly related to the research question to produce practical and pertinent results. For example, weather conditions such as harsh winters or drought years were not explicitly incorporated into the model but were indirectly accounted for through an average non-harvest mortality rate. Likewise, the model maintained a closed population framework, omitting agent immigration and emigration, as the primary objective was to investigate fundamental mechanisms relevant to the research question without introducing unnecessary complexities.

Overview

During *setup*, grid cells adjusted their state variables based on the defined interface selections, which included the town, viewable GIS layers, and relevant agent parameters (e.g., initial deer population, hunting access, etc.). Agents continuously updated their state variables on a weekly basis throughout the entire 10-year simulation, adhering to specific timeframes allocated for each process. For example, submodels like *birth* and *yearling dispersal* were confined to May, while the *rut* was exclusively scheduled for November. Conversely, processes such as WTD aging, movement, and non-hunting mortality occurred during every time step.

Scheduling

The model initiated at the start of the calendar year in January. First, it executed the *setup* process to configure the landscape in accordance with the interface parameters. This *setup* procedure involved clearing the interface from previous runs, establishing initial parameters, creating landscapes and agents as defined by the selection of specifications, and introducing WTD group dynamics to form realistic group structures. In addition to carrying the model forward each week, the *go* procedure was responsible for halting the model under 2 conditions: when there were no deer remaining or when a period of 10 years had elapsed. Additionally, this procedure governed the movements and interactions of agents throughout the landscape. Following each tick (i.e., time step), the model generated outputs on the interface for the user to monitor the desired parameters. The following describes the *setup* and *go* procedures:

- SETUP:
    - Clear all information from previous runs and reset time
    - Create landscape
        - Depict layers according to town selection
        - Apply land access (for hunters and sharpshooters, when applicable)
        - Calculate habitat suitability index (HSI) for deer
    - Create and place agents on model landscape (e.g., WTD, hunters, sharpshooters)
        - Form deer social groups based on coded WTD group dynamics
- GO:
    - Track time (week, month, year, season) each tick
    - Age deer by 1 week each tick
    - Non-harvest mortality based on predetermined sex and age class rates each tick
        - Review groups and select new group leaders if one dies
    - Move deer in home range according to sex, season, and HSI
    - Form bachelor groups after the rut in January
    - Disperse yearlings in May

        - New home range selection based on other group locations
    - Breakdown female groups in May to prepare for fawns
    - Birth new fawns in May according to birth rates
    - New female group formation in October
    - Bachelor group breakdown in preparation for the rut in early November
    - Rut occurs in November
    - Each tick, move hunters/sharpshooters within designated areas, when applicable
    - Hunting mortality from October through December based on access and sex-/age-specific mortality rates, when applicable
    - Sharpshooting mortality occurs in urban zones from January through March, when applicable
    - Outputs are generated at the end of each time step unless otherwise specified
    - Time advances by 1 week

Design Concepts

At the system level, this model addressed a pressing issue in modern WTD management: What is the feasibility of sharpshooting in New England's WTD management system? By exploring the social, ecological, and theoretical foundations of this management paradigm, the model sought to answer this research question and provide unique insights into the feasibility of sharpshooting in the region. While existing literature has tackled this issue, this model offered a unique approach by combining agent-based model analysis with real-world case study data.

Basic Principles

This model operated on both agent and system levels, integrating ecological theory to govern individual WTD behaviors (e.g., dispersal distance, home range size) and the emergent ecological patterns of WTD populations (e.g., mortality rate, population growth). Additionally, it utilized social and political theory at both the agent and system levels to determine the movement and success of hunters, drawing from open access theory (e.g., the availability of hunting land). By combining these theoretical concepts, the model's output contributed to our understanding of natural resource management theory, particularly in the context of WTD sharpshooting feasibility in New England.

Emergence

Some of the key model results that emerged from adaptive decisions and behaviors of agents were: WTD population size, density, and spatial pattern; and hunter and sharpshooter success rates and spatial distributions. These patterns emerged from interactions of hunters, sharpshooters, and management land access, ultimately influencing the dynamics of WTD. Directly related to the research question, these outputs correlated to the efficacy of sharpshooting under diverse social and ecological contexts. Other forms of emergence not directly related to the research question were useful in the validation process, such as WTD sex ratio, age structure, and seasonal behavior.

Adaptation

WTD navigated the landscape based on their HSI which determined how suitable a certain patch was for on a scale from 0.00 to 1.00. For example, high-intensity development areas (e.g., industrial) were assumed completely unsuitable (0.00), open areas were moderately suitable (0.47), and forest was considered highly suitable (0.63) (Flemming et al. 2004, Van Deelen 2023). Within each deer's home range, they chose patches with higher HSIs via direct objective-seeking, though there was a programmed element of randomness in these choices (see *Stochasticity* below). The decision to select a new patch was driven by time (they moved every week) or dispersal. When yearling WTD dispersed in May, they selected their new home range through direct objective seeking based on the location of other groups. They sought to join groups of their same sex (female or bachelor groups) if they had under 20 deer but looked for a new group if there were 20 or more deer (considered group carrying capacity) (Xie et al. 1999, Van Buskirk et al. 2021). Hunters and sharpshooters displayed adaptive behavior through indirect objective seeking by harvesting deer in response to harvest probabilities when deer came within 0.5 mi of hunters or 0.2 mi of sharpshooters during their respective seasons.

Objectives

The objectives of WTD were linked to increasing their fitness, which encompassed their survival and reproductive success. Conversely, hunters and sharpshooters aimed to harvest deer, serving as a population control measure. The rationale behind these objectives was straightforward: WTD naturally strive to survive, while in systems with lethal management, the goal is to harvest deer to manage population levels effectively. Each week during their seasons, hunters and sharpshooters moved within the landscape, and by chance, they came into proximity with a deer that could possibly be harvested. Their movement patterns and responses to cues drove their actions. When yearling WTD dispersed, their objective was to seek a new home range at a particular distance from their natal range. This decision-making process was influenced by their age and sex (Gilbertson et al. 2022). Yearlings sought groups of deer to join, driven by anti-predator instincts and reproductive considerations (Stanke et al. 2018). Consequently, the dispersal distances of deer were influenced by deer density and environmental factors (Piccolo et al. 2000, Fischer et al. 2015). In urban areas and regions with higher deer densities, deer tended to travel greater distances during dispersal (Piccolo et al. 2000, Gilbertson et al. 2022). Although this behavior was assumed to increase individual deer fitness, the model did not explicitly track fitness as an output measure.

Learning

Agents did not encompass mechanisms of learning in this model.

Prediction

WTD generally moved to patches with higher HSI values, implying their prediction of increased fitness. Similarly, yearling WTD used implicit prediction in their patch selection during dispersal, moving towards groups of other deer with the implied expectation of increasing chances of reproduction and reducing the likelihood of predation (Scott C. Williams et al. 2008, Van Deelen 2023).

Sensing

All agents were assumed to have known (sensed) the time of year on a weekly time step, which governed WTD ecology and the presence of hunters and sharpshooters. WTD could also sense the direction they needed to travel to reach higher HSI patches and more suitable areas during dispersal, which was important in representing realistic WTD behavior.

Interaction

WTD directly interacted with each other during the rut, with these interactions determining female pregnancies. Meanwhile, hunters and sharpshooters directly interacted with WTD through harvesting and indirectly interacted by influenced their movement and spatial behaviors. Hunters and sharpshooters could only harvest WTD when they were within areas designated for hunting or sharpshooting; the model did not include poaching or harvest outside legally accessible areas.

Stochasticity

To introduce a realistic element of randomness into the model, various processes were implemented with a degree of stochasticity. During setup, agents were randomly distributed across the landscape in the areas where they could be present (e.g., hunters in open access areas, sharpshooters in urban zones, and deer anywhere). WTD distribution and movement included stochasticity as they chose a high HSI-valued patch in their home range with 30% randomness to represent incorrect decisions, obstacles, interference, or other realistic processes that could interfere with a WTD moving to the most suitable area. Other agent movements also incorporated stochasticity as they selected a new patch each week from their designated areas. All mortalities, whether from natural causes or harvest, were determined using probability distributions based on age and sex. For example, when a deer came within proximity of a hunter, the likelihood of its harvest was higher if it was an adult male compared to a fawn.

Collectives

To represent realistic spatial patterns and social dynamics of WTD, collectives were explicitly portrayed as assemblages of WTD social groups. The group structure changed based on sex and season, with bachelor and female groups forming after the rut and disbanding in preparation for the next rut (Van Deelen 2023). Bachelor groups consisted of up to 6 males and included yearling males once they dispersed in May (Xie et al. 1999, Van Buskirk et al. 2021). Female groups encompassed all females and any of their fawns (up to 20 per group) until the yearlings dispersed in May (Xie et al. 1999, Van Buskirk et al. 2021). These group limits contributed to shaping the emergent spatial arrangement of WTD across the landscape.

Observation

I designed the model to explore how dynamics would change under varying levels of WTD sharpshooting implementation. As a result, the primary outcome of interest was town-scale deer density. The graphical output on the interface tracked summary statistics related to this outcome, along with other data used in the validation process.

Initialization

The model aimed to assess the effects of sharpshooting on system dynamics, specifically, a town's ability to manage their local WTD population. With this goal in mind, during initialization, the user creates the model landscape with the SETUP command. The first step in this process is to clear the interface from all previous model runs and reset any previously recorded information. Then the landscape is created for each town that corresponds to town and selections on the interface. Unless specified otherwise, realistic management, population, and land cover parameters are depicted. Agent parameters (densities, sex/age ratios, etc.) are assigned based on predetermined values calculated for each focal town. Hunters and sharpshooters are initialized in their designates areas (hunters in hunting areas, sharpshooters in urban zones) and are initially hidden but show up later during their respective seasons. Hunters and sharpshooters start with no harvests/culls. WTD are dispersed semi-randomly in social groups within seasonal home ranges and according to their HSI. The model is initialized in the first week of January and runs for 10 years or until there are no deer left.

Input Data

The model does not use input data to represent time-varying processes.

Submodels

I designed the submodels to only include relevant processes to effectively address the research question and focus on the phenomena of interest. The submodels, their details, and their purposes are summarized below.

- SETUP
    - create-landscape: import GIS layers depicting town boundaries, land cover (forest, grassland, open water, wetland, low/medium/high development), estimated management land access areas (huntable areas for hunters and urban zones for sharpshooters), and HSI values for deer.
    - create-agents: create deer, hunters, and sharpshooters when applicable to the management selected, assign densities (all agents), home ranges (deer), social groups (deer) and age/sex distributions (deer), and distribute semi-randomly across landscape in their designated areas (sharpshooters in urban zones, hunters in open access areas, and deer anywhere). Key parameter values are depicted in Tables 24-25.
- GO
    - update-time: advance time by 1 week each tick; track year, month (through get-month Julian calendar), week, and season; update parameters (e.g., seasonal home ranges for deer); and reset relevant parameters (e.g., annual hunter harvest) accordingly.
    - deer-growth: age deer by 1 week each tick.
    - non-harvest-mortality: each tick, deer die based on predetermined probability distributions of sex-, age-, and season-based non-harvest mortality rates (Tables 24-25). Deaths are tracked for each sex and age category, and if a group leader

dies, a new eligible leader (based on age and sex) is randomly selected from that group (Verme 1977, Nelson and Mech 1986, Deelen et al. 1997, Xie et al. 1999, Williams 2008, Van Buskirk et al. 2021).

- move-deer: move each deer to a new random patch within their seasonal home range.
- form-bachelor-groups: in January, bachelor groups form with 1 randomly selected leader (of oldest males) after the rut in groups of 6 or less (Williams 2008, Van Deelen 2023)
- yearling-dispersal: In May, yearlings disperse and select new home ranges based on proximity to conspecifics, prioritizing being in a group but not causing the group to exceed 20 deer (Tables 24-25) (Xie et al. 1999, Van Buskirk et al. 2021, Gilbertson et al. 2022, Van Deelen 2023)
- fawning: in May, bred female deer become pregnant based on pregnancy rates that result in model dynamics aligning with reality, and they change their behavior to solitary for their upcoming fawn birth.
- birth: in May, pregnant females birth 1 fawn; the fawn adopts its mother's home range and its sex is randomly assigned based on a predetermined age distribution (0.51: male, 0.49: female) (Verme 1983, Collier 2004, Van Deelen 2023).
- new-group-formation: in October, females form new groups with other females and their fawns (Xie et al. 1999, Williams 2008, Van Buskirk et al. 2021, Van Deelen 2023).

- <u>mdisperse-before-rut:</u> in November, males disperse before the rut and change their behavior to solitary as they search for a mate (Scott C. Williams et al. 2008, Van Deelen 2023)
- <u>rut:</u> in November, when breeding-age males (> 1.5 years old) come within 3 patches of a female, the female changes her status to bred (Williams 2008).
- <u>move-hunters:</u> move each hunter to new random patch within their town's huntable areas.
- <u>hunting-mortality:</u> hunters harvest deer that are in huntable areas and within 0.5 miles (0.8 km, 27 patches) of their location based on a predetermined sex- and age-based harvest probability distribution (Tables 24-25) (Scott C. Williams et al. 2008, Williams 2008, Norton 2015, NYSDEC (New York State Department of Environmental Conservation) 2019, MassWildlife 2020). Deer deaths and hunter harvest are tracked. When a hunter harvests 2 deer, they switch to hidden and do not harvest any more deer during that season.
- <u>move-sharpshooters:</u> move each sharpshooter to a new random patch within their town's urban zone.
- <u>sharpshooting:</u> sharpshooters harvest deer that are in urban zones and within 0.2 miles (0.3 km, 10 patches) of their location based on an unbiased predetermined cull probability distribution (Tables 24-25) (DeNicola and Williams 2008, Figura 2017*a*). Sharpshooter harvest is tracked, and they do not have a limit on their cull.
- <u>track-output:</u> to facilitate aligning the model with the real-world phenomena of interest through pattern-oriented-modeling, relevant outputs are tracked and displayed on the interface, such as key parameter values, population trackers, and

sex/age distribution monitors (Wilensky and Rand 2015, Railsback and Grimm 2019, Grimm et al. 2020).

Table 24. Town-specific parameter breakdown for the agent-based models, depicting values, definitions, and sources. For clarity to US WTD managers, I adopted imperial units instead of metric (Kelly and Ray 2019).

Town	Pepperell	Lincoln	Carlisle	Weston	Sharon	Easton	Fenner	Manlius	DeWitt	Geddes	Clay
Town Area (mi^2)	23.2	15.0	15.5	17.3	24.2	29.2	31.1	49.9	33.9	12.3	48.9
Hunting Access (%)	20.65	6.03	10.18	11.31	18.00	25.79	63.85	33.22	0.00	0.00	21.00
Hunters (#)	581	222	170	251	416	101	188	183	126	0	155
Hunter Density (#/mi^2)	25.0	14.8	11.0	14.5	17.2	3.5	6.0	3.7	3.7	0.0	3.2
Sharpshooter Density (#/mi^2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.9	3.7	26.0	0.0
Initial Deer (#)	407	504	521	581	731	882	791	1269	862	313	1243
Deer Density (#/mi^2)	17.54	33.60	33.61	33.58	30.21	30.21	25.43	25.43	25.43	25.43	25.43
Harvest Mortality (%)	20	14	14	14	45	45	26	12	9	0	12
Antlerless Harvest Density (#/mi^2)	1.36	1.94	1.94	1.94	5.33	5.33	3.50	1.60	1.27	0.00	1.66
Buck Harvest Density (#/mi^2)	2.24	2.80	2.80	2.80	8.32	8.32	3.09	1.52	0.97	0.00	1.45

Parameter	**Definition**	**Source(s)**
Town Area (mi^2)	Areas calculated for each town in GIS.	GIS
Hunting Access (%)	The estimated percent open hunting access for each town, based on state and local setbacks and restrictions.	GIS
Hunters (#)	Hunter number estimate based on licenses sold in each town.	NYSDEC 2019, MassWildlife 2020
Hunter Density (#/mi^2)	Hunter density estimate based on licenses sold in each town.	NYSDEC 2019, MassWildlife 2020
Sharpshooter Density (#/mi^2)	The density of sharpshooters within the available culling areas.	Data from NYSDEC
Initial Deer (#)	Deer population estimates based on the most recent state wildlife population reconstruction methods.	NYSDEC 2019, MassWildlife 2020
Deer Density (#/mi^2)	Town-level deer density estimates based on population estimate and town area.	NYSDEC 2019, MassWildlife 2020
Harvest Mortality (%)	Deer harvest mortality according to population and harvest estimates.	NYSDEC 2019, MassWildlife 2020
Antlerless Harvest Density (#/mi^2)	Annual harvest density of antlerless deer (females and fawn males).	NYSDEC 2019, MassWildlife 2020
Buck Harvest Density (#/mi^2)	Annual harvest density of bucks.	NYSDEC 2019, MassWildlife 2020

Table 25. Agent-based model parameters, definitions, values, and sources. Values are averages of all focal towns in previous chapters. For clarity to US WTD managers, I adopted imperial units instead of metric (Kelly and Ray 2019).

Parameter	Description	Value	Source(s)
% Female Deer	Percent female deer relative to total deer in the population at time of data output (January 1).	58	Coe et al. 1980, Boulanger et al. 2012
% Male Deer	Percent male deer relative to total deer in the population at time of data output (January 1).	42	Coe et al. 1980, Boulanger et al. 2012
% Fawns	Percent fawn deer relative to total deer in the population at time of data output (January 1).	28.75	Collier 2004
% Yearlings	Percent yearling deer relative to total deer in the population at time of data output (January 1).	23.75	Collier 2004
% Adults	Percent adult deer relative to total deer in the population at time of data output (January 1).	47.5	Collier 2004
% Deer Population Growth	Realized deer population growth from annual spring births with hunting present.	30	Norton 2015, Van Deelen 2023
% Fawn Annual Non-Harvest Mortality	The annual non-harvest mortality percent for fawns relative to deer population.	69	Nelson and Mech 1986
% Yearling Annual Non-Harvest Mortality	The annual non-harvest mortality percent for yearlings relative to deer population.	22.5	Nelson and Mech 1986
% Adult Annual Non-Harvest Mortality	The annual non-harvest mortality percent for adults relative to deer population.	22.5	Nelson and Mech 1986
Fawn/Yearling Harvest %	Annual percentage of fawns and yearlings harvested by hunters relative to the total deer population.	10	Boulanger et al. 2012
Adult Harvest %	Annual percentage of adults harvested relative to the total deer population.	90	Boulanger et al. 2012
Buck Harvest %	Annual percentage of bucks harvested relative to the total deer population.	50	Boulanger et al. 2012
Sharpshooter Harvest Density (#/mi^2)	Annual density of deer culled by sharpshooters when implemented, based on most recent average of 3 towns.	11.8	Data from NYSDEC
Sharpshooter Density (#/mi^2)	Sharpshooter density when implemented in each focal town, based on most recent average of 3 towns.	3.88	Data from NYSDEC

Table 25 (*Continued*). Agent-based model parameters, definitions, values, and sources. Values are averages of all focal towns in previous chapters. For clarity to US WTD managers, I adopted imperial units instead of metric (Kelly and Ray 2019).

Parameter	Description	Value	Source(s)
Male Winter Home Range Radius (mi)	Winter home range for male deer.	2.77	Roden-Reynolds et al. 2022
Male Fall/Spring Home Range Radius (mi)	Fall and spring home range for male deer.	1.83	Roden-Reynolds et al. 2022
Male Summer Home Range Radius (mi)	Summer home range for male deer.	1.31	Roden-Reynolds et al. 2022
Female Winter Home Range Radius (mi)	Winter home range for female deer.	0.59	Roden-Reynolds et al. 2022
Female Fall/Spring Home Range Radius (mi)	Fall and spring home range for female deer.	1.2	Roden-Reynolds et al. 2022
Female Summer Home Range Radius (mi)	Summer home range for female deer.	0.67	Roden-Reynolds et al. 2022

APPENDIX B SOURCES

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APPENDIX C. CHAPTER 4 MODEL DESCRIPTION.

Purpose and Patterns

Purpose

The aim of this model was to investigate the influence of different degrees of coordination in managing white-tailed deer (*Odocoileus virginianus*, henceforth "WTD" or "deer") on system dynamics within New England. In this region, the typical objective of management is to decrease deer populations to alleviate the adverse consequences of deer overabundance. I investigated dynamics of recreational hunting, professional sharpshooting, the combination of hunting and sharpshooting, and no harvest (lack of management). The broad goal of this model was to analyze the impacts of varying levels of management coordination on ecological, social, and theoretical factors at 3 distinct spatial scales.

Patterns

To assess the model's efficacy, my primary focus was on its capacity to simulate realistic fluctuations in hunter, sharpshooter, and WTD population dynamics under varying degrees of management coordination. Additionally, during the validation phase, I analyzed a range of relevant phenomena through pattern-oriented modeling to promote model reliability in depicted the actual system in context of the research questions.

Entities, State Variables, and Scales

Entities

The entities in this model consisted of the observer (determines changing global variables), agents (WTD, hunters, sharpshooters), grid cells (virtual geographic locations), and the global WTD management landscape (population dynamics, coordination levels).

State Variables

The observer controlled global state variables such as year, month, and week. Static observer variables were considered parameters and are defined in the associated submodels. Cells (patches) were the lowest level habitat entity depicting urban zones, huntable areas, and general land cover (unspecified type, same in all towns); variation within cells was not represented. Each cell represented a 2-dimensional horizontal plane, and because their characterization did not change throughout the model, their classifications were treated as state variables instead of parameters. Hunters and sharpshooters did not have any state variables, and WTD could be males or females, and fawns (age < 1 year), yearlings (1 year < age < 2 years), or adults (age > 2 years).

Scales

To portray dynamics at a meaningful level, this model employed continuous weekly time steps starting in January, covering a temporal span of 10 years to illustrate patterns unfolding over a decade. To maintain an agent-based perspective while adhering to practical timeline limitations, this 2-dimensional discrete spatial scale represented towns of approximately 2.7 mi^2 (6.0 km^2), with pixels of 900 m^2 (30 x 30 m). Scale 1 consisted of an isolated town (n = 1, 2.3 mi^2, 6.0 km^2), scale 2 depicted a central town with a layer of 4 adjacent towns (n = 5, 11.5 mi^2, 29.7 km^2), and scale 3 represented a central town with 2 layers of surrounding towns (n = 13, 29.9 mi^2, 77.5 km^2). These fine-scale, bounded landscapes prevented agents from exiting the model's environment, thereby constraining dynamics relevant to the research focus (e.g., population dynamics) while excluding factors like immigration and emigration.

Process, Overview, and Scheduling

Process

The model focused on essential processes involving WTD ecology and behavior, hunter and sharpshooter dynamics, and the varying degrees of management coordination. Notably, the model deliberately excluded processes that were not directly related to the research question to produce practical and pertinent results. For instance, weather conditions such as harsh winters or drought years were not explicitly incorporated into the model but were indirectly accounted for through an average non-hunting mortality rate. Likewise, the model maintained a closed population framework, omitting agent immigration and emigration, as the primary objective was to investigate fundamental mechanisms relevant to the research question without introducing unnecessary complexities.

Overview

During *setup*, grid cells adjusted their state variables based on the defined interface parameters, which included the chosen management strategy, spatial scale, similarity threshold, and relevant agent parameters (e.g., initial deer population, hunting access, etc.). Agents continuously updated their state variables on a weekly basis throughout the entire 10-year simulation, adhering to specific timeframes allocated for each process. For example, submodels like *birth* and *yearling dispersal* were confined to May, while the *rut* was exclusively scheduled for November. Conversely, processes such as WTD aging, movement, and non-hunting mortality occurred during every time step.

Scheduling

The model initiated at the start of the calendar year in January. First, it executed the *setup* process to configure the landscape in accordance with the interface parameters. This *setup* procedure involved clearing the interface from previous runs, establishing initial parameters, creating landscapes and agents as defined by the selection of specifications, and introducing WTD group dynamics to form realistic group structures. In addition to carrying the model forward each week, the *go* procedure was responsible for halting the model under 2 conditions: when there were no deer remaining or when a period of 10 years had elapsed. Additionally, this procedure governed the movements and interactions of agents throughout the landscape. Following each tick (i.e., time step), the model generated outputs on the interface for the user to monitor the desired parameters. The following describes the *setup* and *go* procedures:

- SETUP:
    - Clear all information from previous runs and reset time
    - Create landscape
        - Draw scale (1, 2, or 3)
        - Create management and similarity threshold
            - Assign central management strategy (hunting, sharpshooting, both, no harvest)
            - For scales 2 and 3, assign similar management based on identified threshold (0%, 25%, 50%, 75%, 100%)
        - Apply land access (for hunters and sharpshooters, when applicable)
    - Create and place agents on model landscape (e.g., WTD, hunters, sharpshooters)
        - Form groups based on coded WTD group dynamics

- GO:
    - Track time (week, month, year, season) each tick
    - Age deer by 1 week each tick
    - Non-harvest mortality based on predetermined sex and age class rates each tick
        - Review groups and select new group leaders if one dies
    - Move deer in home range according to sex and season
    - Form bachelor groups after the rut in January
    - Disperse yearlings in May
        - New home range selection based on other group locations
    - Breakdown female groups in May to prepare for fawns
    - Birth new fawns in May according to birth rates
    - New female group formation in October
    - Bachelor group breakdown in preparation for the rut in early November
    - Rut occurs in November
    - Each tick, move hunters/sharpshooters within designated areas, when applicable
    - Hunting mortality from October through December based on access and sex-/age-specific mortality rates, when applicable
    - Sharpshooting mortality occurs in urban zones from January through March, when applicable
    - Outputs are generated at the end of each time step unless otherwise specified
    - Time advances by 1 week

Design Concepts

At the system level, this model addressed a pressing issue in modern WTD management: What role does New England municipal WTD coordination play in influencing dynamics? By exploring the social, ecological, and theoretical foundations of this management system, the model sought to answer this research question and provide unique insights into the theory governing WTD management in the region. While existing literature had also tackled this issue, this model offered a distinctive approach by combining theoretical agent-based model analysis with real-world case study data.

Basic Principles

This model operated on both agent and system levels, integrating ecological theory to govern individual WTD behaviors (e.g., dispersal distance, home range size) and the emergent ecological patterns of WTD populations (e.g., mortality rate, population growth). Additionally, it utilized social and political theory at both the agent and system levels to determine the movement and success of hunters, drawing from open access theory (e.g., the availability of hunting land). By combining these theoretical concepts, the model's output contributed to our understanding of natural resource management theory, particularly in the context of WTD management coordination in New England.

Emergence

Some of the key model results that emerged from adaptive decisions and behaviors of agents were: WTD population size, density, and spatial pattern; and hunter and sharpshooter success rates and spatial distributions. These patterns emerged from interactions of hunters, sharpshooters, and management land access, ultimately influencing the dynamics of WTD. Directly related to the research question, these outputs correlated to the efficacy of management approaches under different paradigms of coordination similarity between towns. Other forms of emergence not directly related to the research question were useful in the validation process, such as WTD sex ratio, age structure, and seasonal behavior.

Adaptation

WTD navigated the landscape by moving to a new patch each week within their seasonal home range. The decision to select a new patch was driven by time (they moved every week) or dispersal. When yearling WTD dispersed in May, they selected their new home range through direct objective seeking based on the location of other groups. They sought to join groups of their same sex (female or bachelor groups) if they had under 20 deer but looked for a new group if there were 20 or more deer (considered group carrying capacity) (Xie et al. 1999, Van Buskirk et al. 2021). Hunters and sharpshooters displayed adaptive behavior through indirect objective seeking by harvesting deer in response to harvest probabilities when deer came within 0.5 mi of hunters or 0.2 mi of sharpshooters during their respective seasons.

Objectives

The objectives of WTD were linked to increasing their fitness, which encompassed their survival and reproductive success. Conversely, hunters and sharpshooters aimed to harvest deer, serving as a population control measure. The rationale behind these objectives was straightforward: WTD naturally strive to survive, while in systems with lethal management, the goal is to harvest deer to manage population levels effectively. Each week during their seasons, hunters and sharpshooters moved within the landscape, and by chance, they came into proximity with a deer that could possibly be harvested. Their movement patterns and responses to cues drove their actions. When yearling WTD dispersed, their objective was to seek a new home range at a particular distance from their natal range. This decision-making process was influenced by their age and sex (Gilbertson et al. 2022). Yearlings sought groups of deer to join, driven by anti-predator instincts and reproductive considerations (Stanke et al. 2018). Consequently, the dispersal distances of deer were influenced by deer density and environmental factors (Piccolo et al. 2000, Fischer et al. 2015). In urban areas and regions with higher deer densities, deer tended to travel greater distances during dispersal (Piccolo et al. 2000, Gilbertson et al. 2022). Although this behavior was assumed to increase individual deer fitness, the model did not explicitly track fitness as an output measure.

Learning

Agents did not encompass mechanisms of learning in this model.

Prediction

Yearling WTD used implicit prediction in their patch selection during dispersal, moving towards groups of other deer with the implied expectation of enhancing their fitness.

Sensing

All agents were assumed to have known (sensed) the time of year on a weekly time step, which governed WTD ecology and the presence of hunters and sharpshooters. WTD could also sense the direction they needed to travel to reach more suitable areas during dispersal, which was important in representing realistic WTD behavior.

Interaction

WTD directly interacted with each other during the rut, with these interactions determining female pregnancies. Meanwhile, hunters and sharpshooters directly interacted with WTD through harvesting and indirectly interacted by influenced their movement and spatial behaviors. Hunters and sharpshooters could only harvest WTD when they were within areas designated for hunting or sharpshooting; the model did not include poaching or harvest outside legally accessible areas.

Stochasticity

To introduce a realistic element of randomness into the model, various processes were implemented with a degree of stochasticity. During setup, agents were randomly distributed across the landscape in the areas where they could be present (e.g., hunters in open access areas, sharpshooters in urban zones, and deer anywhere). Agent movements incorporated stochasticity as they selected a new patch each week from their designated areas. All mortalities, whether from natural causes or harvest, were determined using probability distributions based on age and sex. For example, when a deer came within proximity of a hunter, the likelihood of its harvest was higher if it was an adult male compared to a fawn.

Collectives

To represent realistic spatial patterns and social dynamics of WTD, collectives were explicitly portrayed as assemblages of WTD social groups. The group structure changed based on sex and season, with bachelor and female groups forming after the rut and disbanding in preparation for the next rut (Van Deelen 2023). Bachelor groups consisted of up to 6 males and included yearling males once they dispersed in May (Xie et al. 1999, Van Buskirk et al. 2021). Female groups encompassed all females and any of their fawns (up to 20 per group) until the yearlings dispersed in May (Xie et al. 1999, Van Buskirk et al. 2021). These group limits contributed to shaping the emergent spatial arrangement of WTD across the landscape.

Observation

I designed the model to explore how dynamics would change under varying levels of municipal WTD management coordination. As a result, the primary outcomes of interest included deer density within and outside the central town, as well as deer density in towns implementing lethal management compared to towns without management. The graphical output on the interface tracked summary statistics related to these outcomes, along with other data used in the validation process.

Initialization

The model aimed to assess the effects of management coordination on system dynamics, specifically, a town or region's ability to manage their local WTD population. With this goal in mind, during initialization, the user creates the model landscape with the SETUP command. The first step in this process is to clear the interface from all previous model runs and reset any previously recorded information. Then the landscape is created for each town that corresponds to the scale, management type, and similarity threshold selected on the interface. Landscapes are homogeneous for all towns, except for the spatial pattern of hunting lands. For example, all towns have the same land cover, the same size urban zones, and the same amount of hunting access. The only difference is that, to reflect the real heterogeneous spatial distribution of hunting areas, each town seeds 5 open access patches and grows them to the same percentage of town land covered by open hunting as all other towns. Management type is selected by the user for the central town, and for scales 2 and 3, the similarity threshold dictates the random assignment of management strategies for the remaining towns. The rationale for everything being the same among towns except management strategy is to create a landscape where the single variable of management is changed to isolate and test its impacts. Once the landscape is created, agents are initialized. Agent densities are assigned based on predetermined values from averages of all focal towns in previous chapters. Hunters and sharpshooters are initialized in their designates areas (hunters in hunting areas, sharpshooters in urban zones) and are initially hidden but show up later during their respective seasons. Hunters and sharpshooters start with no harvests/culls. WTD are dispersed semi-randomly in social groups within seasonal home ranges. The model is initialized in the first week of January and runs for 10 years or until there are no deer left.

Input Data

The model does not use input data to represent time-varying processes.

Submodels

I designed the submodels to only include relevant processes to effectively address the research question and focus on the phenomena of interest. The submodels, their details, and their purposes are summarized below.

- SETUP
  - <u>create-scales</u>: depict towns in scales 1, 2, or 3 depending on interface selection, and apply unique color to each town for clarity on the interface.
  - <u>create-similarity</u>: assign similarity randomly to towns based on central management strategy (hunting, sharpshooting, both lethal, no harvest) and similarity (0%, 25%, 50%, 75%, 100%) selection on interface. Create labels for management of each town.
  - <u>create-access</u>: designate areas where hunters can harvest deer based on interface selection of percent of town lands open to hunting. All towns seed 5 patches of

access and grow huntable areas until all towns have the same percent access according to the selected percent.

  - create-urban-areas: define urban zones in the center of each town for sharpshooters based on interface selection of low, medium, or high sharpshooter access.
  - create-agents: create deer, hunters, and sharpshooters when applicable to the management strategy selected, assign densities (all agents), home ranges (deer), social groups (deer) and age/sex distributions (deer), and distribute semi-randomly across landscape in their designated areas (sharpshooters in urban zones, hunters in open access areas, and deer anywhere). Key parameter values are depicted in Table 26.

- GO
  - update-time: advance time by 1 week each tick; track year, month (through get-month Julian calendar), week, and season; update parameters (e.g., seasonal home ranges for deer); and reset relevant parameters (e.g., annual hunter harvest) accordingly.
  - deer-growth: age deer by 1 week each tick.
  - non-harvest-mortality: each tick, deer die based on predetermined probability distributions of sex-, age-, and season-based non-harvest mortality rates (Table 26). Deaths are tracked for each sex and age category, and if a group leader dies, a new eligible leader (based on age and sex) is randomly selected from that group (Verme 1977, Nelson and Mech 1986, Deelen et al. 1997, Xie et al. 1999, Williams 2008, Van Buskirk et al. 2021).

- move-deer: move each deer to a new random patch within their seasonal home range.
- form-bachelor-groups: in January, bachelor groups form with 1 randomly selected leader (of oldest males) after the rut in groups of 6 or less (Williams 2008, Van Deelen 2023)
- yearling-dispersal: In May, yearlings disperse and select new home ranges based on proximity to conspecifics, prioritizing being in a group but not causing the group to exceed 20 deer (Table 26) (Xie et al. 1999, Van Buskirk et al. 2021, Gilbertson et al. 2022, Van Deelen 2023)
- fawning: in May, bred female deer become pregnant based on pregnancy rates that result in model dynamics aligning with reality, and they change their behavior to solitary for their upcoming fawn birth.
- birth: in May, pregnant females birth 1 fawn; the fawn adopts its mother's home range and its sex is randomly assigned based on a predetermined age distribution (0.51: male, 0.49: female) (Verme 1983, Collier 2004, Van Deelen 2023).
- new-group-formation: in October, females form new groups with other females and their fawns (Xie et al. 1999, Williams 2008, Van Buskirk et al. 2021, Van Deelen 2023).
- mdisperse-before-rut: in November, males disperse before the rut and change their behavior to solitary as they search for a mate (Scott C. Williams et al. 2008, Van Deelen 2023)
- rut: in November, when breeding-age males (> 1.5 years old) come within 3 patches of a female, the female changes her status to bred (Williams 2008).

- move-hunters: move each hunter to new random patch within their town's huntable areas.
- hunting-mortality: hunters harvest deer that are in huntable areas and within 0.5 miles (0.8 km, 27 patches) of their location based on a predetermined sex- and age-based harvest probability distribution (Table 26) (Scott C. Williams et al. 2008, Williams 2008, Norton 2015, NYSDEC (New York State Department of Environmental Conservation) 2019, MassWildlife 2020). Deer deaths and hunter harvest are tracked. When a hunter harvests 2 deer, they switch to hidden and do not harvest any more deer during that season.
- move-sharpshooters: move each sharpshooter to a new random patch within their town's urban zone.
- sharpshooting: sharpshooters harvest deer that are in urban zones and within 0.2 miles (0.3 km, 10 patches) of their location based on an unbiased predetermined cull probability distribution (Table 26) (DeNicola and Williams 2008, Figura 2017*a*). Sharpshooter harvest is tracked, and they do not have a limit on their cull.
- track-output: to facilitate aligning the model with the real-world phenomena of interest through pattern-oriented-modeling, relevant outputs are tracked and displayed on the interface, such as key parameter values, population trackers, and sex/age distribution monitors (Wilensky and Rand 2015, Railsback and Grimm 2019, Grimm et al. 2020).

Table 26. Theoretical agent-based model parameters, definitions, values, and sources. Values are averages of all focal towns in previous chapters. For clarity to US WTD managers, I adopted imperial units instead of metric (Kelly and Ray 2019).

Parameter	Description	Value	Source(s)
Female Deer (%)	Percent female deer relative to total deer in the population at time of data output (January 1).	58.0	Coe et al. 1980, Boulanger et al. 2012
Male Deer (%)	Percent male deer relative to total deer in the population at time of data output (January 1).	42.0	Coe et al. 1980, Boulanger et al. 2012
Fawns (%)	Percent fawns relative to total deer in the population at time of data output (January 1).	28.8	Collier 2004
Yearlings (%)	Percent yearlings relative to total deer in the population at time of data output (January 1).	23.8	Collier 2004
Adults (%)	Percent adults relative to total deer in the population at time of data output (January 1).	47.5	Collier 2004
Deer Population Growth (%)	Realized deer population growth from annual spring births with hunting present.	30.0	Norton 2015, Van Deelen 2023
Fawn Annual Non-Harvest Mortality (%)	Annual non-harvest mortality percent for fawns relative to deer population.	69.0	Nelson and Mech 1986
Yearling Annual Non-Harvest Mortality (%)	Annual non-harvest mortality percent for yearlings relative to deer population.	22.5	Nelson and Mech 1986
Adult Annual Non-Harvest Mortality (%)	Annual non-harvest mortality percent for adults relative to deer population.	22.5	Nelson and Mech 1986
Fawn/Yearling Harvest (%)	Annual percentage of fawns and yearlings harvested by hunters relative to the total deer population.	10.0	Boulanger et al. 2012
Adult Harvest (%)	Annual percentage of adults harvested relative to the total deer population.	90.0	Boulanger et al. 2012
Buck Harvest (%)	Annual percentage of bucks harvested relative to the total deer population.	50.0	Boulanger et al. 2012
Sharpshooter Harvest Density (#/mi^2)	Annual density of deer culled by sharpshooters when implemented, based on most recent average of 3 towns.	11.8	Data from NYSDEC
Sharpshooter Density (#/mi^2)	Sharpshooter density when implemented in each focal town, based on most recent average of 3 towns.	3.9	Data from NYSDEC
Town Area (mi^2)	Average area of focal towns (27.3 mi^2) divided by 10 (for practicality*)	2.7	GIS
Hunting Access (%)	Average estimated percent open hunting access for all focal towns, based on state and local setbacks and restrictions.	21.0	GIS
Hunters (#)	Average hunter number per town* based on licenses sold in each town.	43	NYSDEC 2019, MassWildlife 2020

Table 26 (*Continued*). Theoretical agent-based model parameters, definitions, values, and sources. Values are averages of all focal towns in previous chapters. For clarity to US WTD managers, I adopted imperial units instead of metric (Kelly and Ray 2019).

Parameter	Description	Value	Source(s)
Hunter Density (#/mi^2)	Average hunter density estimate of town based on licenses sold in each town.	15.6	NYSDEC 2019, MassWildlife 2020
Initial Deer (#)	Average initial deer population per town* based on most recent estimates.	407	NYSDEC 2019, MassWildlife 2020
Deer Density (#/mi^2)	Average town-level deer density based on population estimate and town area.	17.5	NYSDEC 2019, MassWildlife 2020
Harvest Mortality (%)	Average deer harvest mortality according to population and harvest estimates.	20	NYSDEC 2019, MassWildlife 2020
Antlerless Harvest Density (#/mi^2)	Average annual harvest density of antlerless deer (females and fawn males).	1.36	NYSDEC 2019, MassWildlife 2020
Buck Harvest Density (#/mi^2)	Average annual harvest density of bucks.	2.24	NYSDEC 2019, MassWildlife 2020
Male Winter Home Range Radius (mi)	Winter home range for male deer.	2.77	Roden-Reynolds et al. 2022
Male Fall/Spring Home Range Radius (mi)	Fall and spring home range for male deer.	1.83	Roden-Reynolds et al. 2022
Male Summer Home Range Radius (mi)	Summer home range for male deer.	1.31	Roden-Reynolds et al. 2022
Female Winter Home Range Radius (mi)	Winter home range for female deer.	0.59	Roden-Reynolds et al. 2022
Female Fall/Spring Home Range Radius (mi)	Fall and spring home range for female deer.	1.2	Roden-Reynolds et al. 2022
Female Summer Home Range Radius (mi)	Summer home range for female deer.	0.67	Roden-Reynolds et al. 2022

*I reduced population numbers (#) by a factor of 10 while preserving percentages (%) and densities (#/mi^2) to maintain model feasibility.

APPENDIX C SOURCES

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