# White-tailed Deer Management in the 21st Century

A Conceptual Synthesis of Population Modeling and Decision Frameworks

White-tailed deer (Odocoileus virginianus) represent both a remarkable conservation success and one of the most pressing wildlife management challenges in North America. By the early 20th century, unregulated market hunting and widespread habitat conversion had reduced populations to fewer than 500,000 individuals, with deer nearly extirpated from much of the eastern United States (McCabe & McCabe 1984; Trefethen 1970). Through the establishment of protective legislation, restocking programs, and the development of wildlife management agencies funded primarily by hunters, deer populations rebounded dramatically. By the end of the 20th century, many states reported record-high densities, and deer had become both ecologically influential and culturally embedded across the landscape (Hewitt 2015; McShea 2012; Cook & Gray 2003).

This recovery, however, has created a paradox, where conservation frameworks that were designed to restore deer from scarcity have proven ill-suited for the management of overabundant populations, especially in the densely settled landscapes of the East. In these regions, deer exert strong ecological effects as keystone herbivores, shaping forest regeneration, understory diversity, and faunal communities (Waller & Alverson 1997; Côté et al. 2004; Schwegmann et al. 2024). At the same time, deer support state agency budgets through hunting revenues, provide a food source and cultural identity, and connect generations through hunting traditions (Hewitt 2015). Yet these benefits are increasingly offset by conflicts: agricultural and forestry damage, over one million deer–vehicle collisions annually in the United States (Scofield et al. 2002), and growing concerns about zoonotic disease and public safety. Deer thus embody the tension between ecological, economic, and cultural values more than perhaps any other North American species.

The management of deer in the 21st century faces a set of interconnected challenges that extend far beyond population abundance. Declines in hunter participation, particularly acute in the eastern United States where access is restricted and demographics are shifting, threaten the financial and political foundations of traditional management (Enck et al. 2003; Diefenbach et al. 2021). The emergence and spread of chronic wasting disease (CWD) and other epizootics not only undermine confidence in agencies but also complicate the use of hunter harvest as a regulatory tool (Needham et al. 2007). Climate change is altering deer distribution and habitat use, favoring further expansion into northern forests (Dawe & Boutin 2016), while high densities increase risk of zoonotic spillover such as Lyme disease, especially in suburban landscapes (White & Ward 2010). These dynamics interact: disease reduces hunter trust, declining hunters limit agency options, and climate change reshapes the ecological context, producing a system defined less by single drivers than by their interdependence.

At the same time, technological advances are transforming the data landscape. Camera traps, drones, telemetry, and citizen science provide unprecedented volumes of ecological information, while machine learning and cloud-based computing make it possible to integrate and analyze these diverse datasets at scale (Allan et al. 2018; Besson et al. 2022; Ellis Soto et al. 2025). Yet barriers of cost, expertise, and skepticism toward “black box” approaches remain, especially for state agencies in the East with limited budgets and high management expectations (Ditchkoff & Belsare 2025). A key insight is that data abundance does not automatically translate to management capacity: what matters is whether tools are reproducible, transparent, and accessible to practitioners.

Frameworks for decision-making remain fragmented. Mechanistic and hybrid models (Xie et al. 1999), harvest-based sex-age-kill models (Diefenbach & Shea 2011), and emerging integrated population models (Gaya et al. 2025) have advanced the field, yet rarely are they implemented in ways that are reproducible, transferable, and adaptable to local contexts (Brandell et al. 2022). In the eastern U.S., where deer abundance is entangled with complex social and ecological systems, reliance on politically defined management units and non-standardized data further constrains adaptive management (Diefenbach et al. 2021). The gap is not only technical but conceptual: management frameworks have not evolved in pace with the challenges they are meant to address.

The legacy of the 20th century, restoring deer under the North American Model of Wildlife Conservation, created stability but also embedded assumptions of growth and hunter centrality. Today, that legacy is ill-suited to navigating modern realities of overabundance, zoonoses, climate pressures, and shifting societal values. The crossroads metaphor underscores two possible futures: one where agencies continue to operate within outdated paradigms and risk losing relevance, and another where deer serve as a testbed for rethinking wildlife governance.

Our objective is to develop a conceptual synthesis with perspective, moving beyond review to highlight how white-tailed deer reveal broader lessons for wildlife management. Specifically, we argue that the future requires: Integrative frameworks linking ecological, social, and public health dimensions, reproducible and accessible tools that democratize technological advances such as cloud computing and citizen science, adaptive governance approaches that incorporate diverse stakeholder values beyond hunting constituencies, and a shift from a growth-oriented paradigm to one emphasizing resilience, legitimacy, and adaptability. By situating white-tailed deer management within the crossroad between their emblematic role in conservation and contemporary challenges, we propose that this species is more than a management challenge, it is a conceptual bridge to understanding how conservation in North America must evolve in the 21st century.

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White-tailed deer (Odocoileus virginianus) occupy a paradoxical position in North American conservation. They are simultaneously one of the continent’s most celebrated conservation success stories and among the most difficult management challenges of the present day. From near extirpation in the late 19th century, deer populations rebounded dramatically through coordinated legislation, restocking programs, and hunter-funded conservation systems (McCabe & McCabe 1984; Trefethen 1970; Hewitt 2015). Today, populations are stable or increasing across much of the United States, particularly in the East, where deer densities far exceed historical baselines (Cook & Gray 2003; Hanberry & Hanberry 2020; McShea 2012). Yet this triumph of recovery has generated a new crisis, one of overabundance, ecological disruption, human–wildlife conflict, and eroding legitimacy of traditional management tools. We contend that deer management in the 21st century represents a crossroads: the conservation frameworks and tools that successfully addressed scarcity are increasingly ill-suited for addressing abundance, disease, climate change, and shifting societal values. This introduction situates white-tailed deer as both a case study and a conceptual bridge for rethinking wildlife management. By synthesizing historical trajectories, ecological roles, socio-cultural dimensions, emerging challenges, technological advances, and governance frameworks, we argue that deer management provides critical lessons for the future of conservation in the United States.

By the late 1800s, white-tailed deer had been nearly extirpated across the eastern United States. Overhunting, market demand, deforestation, and agricultural expansion reduced national populations to fewer than 500,000 individuals (McCabe & McCabe 1984). In Alabama, estimates placed the statewide population at ~2,000 individuals in the early 20th century (Cook & Gray 2003). Similar declines were recorded throughout the Southeast, with most states reaching their lowest numbers between 1915 and 1925 (Barick 1951). The recovery of deer in the 20th century was one of the great conservation success stories. The passage of the Lacey Act (1900) curtailed interstate market hunting, while the Pittman–Robertson Act (1937) provided sustainable federal funding for wildlife agencies through excise taxes on firearms and ammunition (Hewitt 2015; Trefethen 1970). State agencies and private landowners engaged in extensive restocking programs, with more than 105,000 deer translocated after 1937 (Hewitt 2015). Game preserves, refugia, and federal lands served as reservoirs from which populations expanded (Hanberry & Hanberry 2020). By the end of the century, white-tailed deer numbered in the tens of millions, with Alabama alone supporting 1.75 million animals by 2000 (Cook & Gray 2003).

This restoration was facilitated by the North American Model of Wildlife Conservation (NAM), which positioned wildlife as a public trust resource and tied state agencies to hunting revenues as their primary funding source (McShea 2012; Hewitt 2015). In the context of scarcity, the NAM provided a clear mandate to grow game populations to support recreational hunting. However, this same mandate has proven far less effective in addressing the contemporary challenges of abundance.

White-tailed deer are a keystone herbivore in eastern forests, shaping forest regeneration, understory composition, and faunal communities through selective browsing (Waller & Alverson 1997; Côté et al. 2004; Schwegmann et al. 2024). Chronic browsing suppresses regeneration of oaks and hemlocks, homogenizes understory vegetation, and facilitates invasive plant expansion (Gill 2001; Ammer 1996; Parker et al. 2006). Yet deer also provide important ecological services, including seed dispersal, nutrient cycling, and serving as prey for large carnivores (Hewitt 2015; Bardgett & Wardle 2003). Economically, deer hunting remains the financial cornerstone of state wildlife agencies. Revenues from license sales and excise taxes fund the majority of management budgets, especially in the East where deer are the most pursued big game species (McShea 2012; Hewitt 2015). Deer hunting also contributes billions of dollars annually to rural economies through equipment sales, travel, and associated expenditures. Socially and culturally, deer remain deeply embedded in rural traditions. Hunting is an autumn ritual that sustains family bonds, cultural identity, and food security across much of the East (Hewitt 2015). Support for deer hunting as a food source remains high, even among non-hunters, with surveys reporting ~85% approval (Hewitt 2015). Yet in suburban and exurban contexts, deer increasingly represent conflict. Safety concerns, firearm restrictions, and divergent social attitudes often limit hunting, leading to localized overabundance (Urbanek et al. 2011). Deer–vehicle collisions exceed 1.5 million annually nationwide, costing over $1 billion in damages (Scofield et al. 2002). These ecological, economic, and social dimensions illustrate that deer are not just a species to be managed but a nexus of values and conflicts, embodying the tensions of modern wildlife governance.

The management of deer today is shaped by a complex asssemblage of interdependent challenges. The number of hunters in the U.S. has been steadily declining for decades, with the most acute impacts in eastern states where land access is restricted and hunting demographics are aging (Enck et al. 2003; Diefenbach et al. 2021). Recruitment, retention, and reactivation programs (R3) have sought to broaden participation, especially among women and non-traditional hunters (Pollan 2006; Price Tack et al. 2018), but overall declines persist. With hunting central to both agency funding and population control, this decline threatens management capacity. Diseases such as chronic wasting disease (CWD) has expanded steadily eastward, undermining the use of harvest as a population control tool and eroding public trust (Needham et al. 2007). Other regionally important diseases include bovine tuberculosis in Michigan and epizootic hemorrhagic disease (EHD) across the Southeast (McShea 2012). These diseases complicate both management logistics and public perceptions. Deer densities influence zoonotic spillover risk, particularly through interactions with ticks and Lyme disease (Scofield et al. 2002; White & Ward 2010). As suburban landscapes expand, deer–human contact intensifies, creating both ecological and health-related conflicts. The COVID-19 pandemic has further underscored concerns about wildlife reservoirs and management legitimacy. Deer are favored by milder winters, altered forest composition, and agricultural expansion in the East. Climate-driven shifts are facilitating range expansion northward (Dawe & Boutin 2016), while exacerbating ecological impacts in existing habitats (Côté et al. 2004). Disease undermines hunter confidence; declining hunters limit agency capacity; climate change magnifies ecological impacts; and public health risks shift social attitudes. Deer management is thus not only a question of biology, but a complex socio-ecological system defined by feedback loops and interdependence.

Advances in ecological monitoring are transforming the information available for deer management. Camera traps and N-mixture models now provide abundance estimates in dense forests (Keever et al. 2017). Telemetry and GPS collars reveal fine-scale movement and habitat use, including in fragmented suburban landscapes. Remote sensing, LiDAR, drones, and acoustic monitoring allow non-invasive tracking of ecological change (Besson et al. 2022). Citizen science platforms such as iNaturalist and eBird generate taxonomically broad, cost-effective datasets that capture deer impacts across public and private lands (Ellis Soto et al. 2025). Perhaps most importantly, cloud-based computing and machine learning pipelines are revolutionizing data management. Distributed computing reduces barriers of local storage and processing power, facilitates cross-agency collaboration, and enables reproducible workflows (Allan et al. 2018; Besson et al. 2022). These tools make it possible to integrate camera trap images, telemetry, harvest data, and citizen science records at scales previously unimaginable.Yet the potential of these tools is constrained by practical barriers. Agencies face budget limitations, uneven technical expertise, and skepticism toward “black box” modeling approaches (Ditchkoff & Belsare 2025). As a result, technological advances risk creating a divide between academic research and management practice. The critical question is not whether new data streams exist, but whether they are accessible, transparent, and adaptable for practitioners.

A variety of frameworks exist for deer management, but none fully address the needs of 21st-century systems. Hybrid mechanistic and empirical models evaluate effects of management scenarios (Xie et al. 1999). Harvest-based sex-age-kill models remain common in state agencies (Diefenbach & Shea 2011). Agent-based models simulate landscape-level dynamics of deer and humans (Castle & Crooks 2006). More recently, integrated population models (IPMs) combine demographic and harvest data for greater precision (Gaya et al. 2025). However, these frameworks suffer from limitations. Harvest data are often fragmented and non-standardized across states (Brandell et al. 2022). Models are frequently not reproducible, transferable, or usable by managers without specialized training (Ditchkoff & Belsare 2025). In the eastern U.S., management units are often politically rather than ecologically defined, further constraining adaptive capacity (Diefenbach et al. 2021). However we observe a gap between the powerful tools exist in theory but are not consistently implemented in practice. The emerging necessity for reproducible, precise, locally relevant, and accessible decision frameworks that integrate multiple data sources, balance trade-offs across objectives, and are adaptable to diverse management contexts. Such frameworks would enable agencies to move beyond reactive crisis management toward proactive, transparent, and participatory governance.

The case of white-tailed deer demonstrates both the strengths and limitations of the North American Model of Wildlife Conservation. The NAM was instrumental in restoring game populations from scarcity, but it remains oriented toward growth, hunter centrality, and consumptive values (McShea 2012; Hewitt 2015). In the East, where deer are abundant and hunters are declining, this orientation no longer reflects ecological realities or societal expectations. We argue that deer management should be reframed as a testbed for adaptive governance. This involves integrating ecological science with public health, sociology, and climate adaptation; democratizing access to monitoring tools and data; and embedding decision-making within transparent, reproducible, and participatory frameworks. Adaptive governance recognizes that deer are not only a wildlife resource but also a source of ecological risk, economic cost, and cultural value.

Deer management in the 21st century is at a crossroads. The legacy of the 20th century, scarcity-driven conservation under the North American Model, created stability but embedded assumptions that no longer hold. The reality of the 21st century, overabundant populations, zoonotic risks, climate pressures, and declining hunters, requires innovation in both science and governance.

This paper contributes a conceptual synthesis with perspective. We highlight how deer management illustrates broader issues of wildlife governance in North America: the need for integrative frameworks, reproducible and accessible tools, adaptive governance structures, and a rebalancing of ecological, economic, and cultural values. By situating deer at the nexus of these challenges, we argue that they are not only a management problem but also a conceptual bridge for envisioning the future of conservation in the United States. The crossroads highlighted outlines the potential outcomes of contemporary management and deer populations based on reliance on outdated paradigms and reactive management, risking ecological degradation and loss of legitimacy or toward integrative, adaptive, and pluralistic governance, in which deer serve as a model system for rethinking wildlife conservation in the 21st century.

Outline

**Introduction and Rationale**

* Deer as socio-ecological linchpins
  + White-tailed deer (*Odocoileus virginianus*) function as keystone herbivores, altering forest regeneration and biodiversity (Waller & Alverson 1997; Côté et al. 2004), while simultaneously sustaining hunting traditions and providing essential revenue streams under the North American Model of Wildlife Conservation (NAM) (Heffelfinger et al. 2013; McShea 2012; Hewitt 2015).
* Duality of deer populations
  + *Positive*: ecological roles (seed dispersal, nutrient cycling), hunting culture, financial backbone of agencies (AFWA 2017).
  + *Negative*: vehicle collisions (>1.5M annually; Bissonette et al. 2008), crop/forest losses (Bleier et al. 2012), and zoonotic disease risk (White & Ward 2010; Martin et al. 2011).
* Turning point in management
  + 20th century: *scarcity and recovery* → legislation, translocations, restoration.
  + 21st century: *abundance and conflict* → disease emergence, hunter decline, climate change, sociopolitical contestation (Diefenbach et al. 2025; Logan et al. 2025).
* Perspective
  + Contemporary deer challenges are both the *product and continuation* of the NAM paradigm established a century ago. While NAM prevented extirpation and built legitimacy through hunter funding, it now constrains adaptation to 21st-century stressors (Artelle et al. 2018; McShea 2012).
  + Management challenges of deer are *emblematic of broader constraints faced by wildlife agencies*: limited labor, shrinking budgets, constrained time, and mounting societal pressures (Diefenbach et al. 2025).
  + Though scarcity has not defined deer populations in the 21st century, the *pace of new ecological, social, and technological challenges* underscores the urgency of a management transition.
* Objectives
  + The primary objective of this chapter is to synthesize the historical, ecological, and sociopolitical contexts that define white-tailed deer management in the 21st century, and to outline the rationale for developing modeling, monitoring, and decision-analysis frameworks capable of meeting contemporary challenges. Specifically, this chapter aims to:
    - 1. Review the historical evolution of deer management in North America, from recovery-era strategies to present-day complexities.
    - 2. Identify the limitations of legacy monitoring and modeling frameworks under current ecological and social conditions.
    - 3. Describe the potential of pluralistic, integrative modeling approaches to improve inference, transparency, and decision-making capacity.
    - 4. Establish a conceptual foundation for subsequent chapters, which will evaluate specific modeling approaches, assess their performance under varying data conditions, and explore their application to real-world management contexts.
  + In doing so, this chapter aligns with the broader goal of producing a defensible, adaptable decision-making framework that integrates diverse data sources, employs multiple modeling tools, and can be applied across spatial scales to inform harvest

**Historical Foundations of Deer Management**

* Exploitation and Collapse (pre-1900s)
  + Unregulated market hunting, deforestation, and agriculture reduced U.S. deer populations to <500,000 (McCabe & McCabe 1984; Trefethen 1970).
  + In Alabama, numbers declined to ~2,000 (Cook & Gray 2003).
* Recovery and Restoration (1900s–1950s)
  + Lacey Act (1900) and Pittman–Robertson Act (1937) institutionalized recovery (Trefethen 1970; Hewitt 2015).
  + Translocation (>105,000 deer in East) drove repopulation (Hanberry & Hanberry 2020).
  + NAM entrenched hunters as the constituency and funders of conservation (McShea 2012).
* Expansion and QDM (1970s–2000s)
  + exploded; Alabama reached ~1.75M by 2000 (Cook & Gray 2003).
  + Ecological impacts: oak regeneration failure, understory simplification (Tilghman 1989; Parker et al. 2006).
  + Rise of QDM emphasized antler restrictions, antlerless harvests, and cooperative private land management (McShea 2012).
* Contemporary Era (2010s–present)
  + Challenges: CWD, EHD, TB; climate-driven range expansion; hunter aging and decline; stakeholder polarization (Needham et al. 2007; Dawe & Boutin 2016; Diefenbach et al. 2025).
* Legacy: NAM built resilience but tied funding and legitimacy to hunter participation, now eroding (Artelle et al. 2018).

**Deer Population Values and Trade-offs**

* Ecological
  + Keystone role: browsing alters regeneration, shifts successional dynamics, and facilitates invasive species (Gill 2001; Côté et al. 2004).
  + *Positive*: dispersal, nutrient cycling (Bardgett & Wardle 2003).
  + *Negative*: homogenization of understories, biodiversity loss (Schwegmann et al. 2024).
* Economic
  + License sales + excise taxes fund >50% of wildlife agency budgets (AFWA 2017).
  + Costs: >$1B annually in deer–vehicle collisions and crop/forest losses (Scofield et al. 2002; Bleier et al. 2012).
* Sociocultural
  + Hunting as a cultural touchstone, with broad approval for food-based harvests (Hewitt 2015).
  + Declining participation (~20% since 2011) and aging demographics narrow the constituency (USFWS & USCB 2018; Diefenbach et al. 2025).
* Perspective: Divergence across geography
  + Midwest: hunter satisfaction and harvest optimization dominate.
  + Northeast: Lyme disease, suburban conflicts, forest regeneration.
  + Southeast: agency funding and hunter participation central.
  + These variations underscore the need for generalizable but locally adaptable frameworks.

**Contemporary Management Challenges**

* Sociocultural pressures
  + Demographic stagnation: hunters ≥90% male, ≥97% white (USFWS & USCB 2018).
  + Urbanization reduces access, compounding participation declines (Enck et al. 2003).
  + R3 programs fail to offset long-term attrition (Pollan 2006; Price Tack et al. 2018).
* Disease and Public Health
  + CWD reduces hunter trust and agency legitimacy (Needham et al. 2007; Holsman et al. 2010).
  + Other zoonoses: Lyme, SARS-CoV-2 reservoirs, EHD (White & Ward 2010; Logan et al. 2025).
  + Public health dimension expands deer management beyond ecology.
* Climate and Environmental Change
  + Northern range expansion accelerated by warming winters (Dawe & Boutin 2016).
  + Land-use changes (fragmentation, suburban sprawl) sustain high densities (Hanberry 2021).
* Institutional Constraints
  + Management units often follow political rather than ecological boundaries (Rosenberry & Diefenbach 2019).
  + Harvest-based monitoring increasingly unfit under declining hunter participation (Diefenbach & Shea 2011).
  + Agencies face growing mistrust, litigation, and societal polarization (Artelle et al. 2018).

**Monitoring and Data Systems**

* Traditional
  + Harvest-based indices (SAK, SPR) remain dominant (Cook & Gray 2003; Diefenbach & Shea 2011).
  + Strengths: inexpensive, long time series. Limitations: hunter dependence, effort biases.
* Emerging
  + Camera surveys with N-mixture models (Keever et al. 2017).
  + Roadkill/incidental mortality monitoring (Logan et al. 2025).
  + Telemetry/GPS collars for movement and disease ecology (Wallingford et al. 2017).
* Integration opportunities
  + Double-sampling: broad harvest/citizen science data linked to intensive local monitoring (Besson et al. 2022).
  + Participatory integration: hunter-led camera programs or agency–researcher collaborations enhance legitimacy (Ellis Soto et al. 2025).
* VI. Analytical and Technological Advances
* Traditional models: SAK, SPR, matrix approaches remain widespread (Diefenbach & Shea 2011).
* Modern advances
  + Bayesian state-space models integrate multiple datasets and uncertainty (Dietze et al. 2018).
  + Integrated Population Models (IPMs) combine harvest, telemetry, surveys (Gaya et al. 2025).
  + ABMs simulate spatial harvest, disease, land-use change (Xie et al. 1999; Castle & Crooks 2006).
* Technological enablers
  + Drones, automated sensors, ML pipelines (Allan et al. 2018; Besson et al. 2022).
  + Cloud-based workflows democratize access (R, GitHub, Shiny dashboards) (Ditchkoff & Belsare 2025).
* Barriers
  + Lack of technical training, financial constraints, mistrust of “black box” models (Pedroso de Lima et al. 2020).
  + Data heterogeneity among states limits comparability.

**Toward a Standardized Decision-Making Framework**

* Rule of 3: No model answers all questions; complementary tools required (Castle & Crooks 2006; Diefenbach et al. 2021).
* Accessibility
  + Framework requires minimal technical expertise and no specialized data inputs.
  + Strength lies in *interpretability* for managers, not in computational sophistication.
  + *Caveat*: The quality of decisions depends on participatory engagement with agency staff and biologists; limited data situations especially require expert input to contextualize models.
* Perspective
  + North America lacks a multi-modeling system that is:
    - *Precise*, capable of generating defensible outputs under uncertainty.
    - *Generalizable*, adaptable across ecological regions and institutional structures.
    - *Accessible*, transparent, reproducible, and usable by practitioners.
  + Geographic variation in deer ecology, differences in societal impacts, and diversity in agency funding and stakeholder relationships preclude a one-size-fits-all model.
* Future direction
  + Pluralistic frameworks must merge SAK/SPR, Bayesian models, IPMs, ABMs, and citizen science inputs.
  + Explicit articulation of assumptions, uncertainty, and trade-offs is essential (Artelle et al. 2018).
  + Framework must serve as both an analytical tool and a participatory platform that democratizes decision-making.

**Current Crossroads**

* 20th-century scarcity yielded today’s overabundance and ecological conflict.
* Agencies now confront unprecedented challenges: emergent disease, hunter decline, climate change, and societal polarization.
* These pressures reflect not just ecological dynamics but the institutional legacy of NAM and structural constraints of wildlife agencies.
* Perspective: Without a pluralistic, accessible, and generalizable decision-making framework, deer management risks remaining reactive, fragmented, and poorly suited for the rapid pace of 21st-century change.

LITERATURE REVIEW

## . Justification & Background

* Most important variables and importance value (if ≥50) for random forests and extreme gradient boosting (egb) models of deer densities (low- density class < 5.8 deer/km2, moderately low to high- density class ≥5.8 deer/km2, low and moderately low- density class <11.6 deer/km2, and moderately high and high- density class ≥11.6 deer/km2) by region - Hanberry BB, 2021
* We note that societal interest in how domestic animals are raised and processed has increased interest in wild game as a source of protein and this interest has, in part, increased hunting participation by non-traditional hunters, especially women (Pollan 2006). In addition, many state agencies are engaged in efforts to recruit and retain hunters (Price Tack et al. 2018). However , we identi fied declining trends in hunter numbers as an important factor that will determine the future and importance of deer hunting to achieve social, ecological, and disease - related management objectives. - Diefenbach D et al., 2021
* However, in areas with limited mortality factors other than hunting, declining hunter participation and harvest will create significant challenges. Such challenges have existed in urban and suburban areas for decades where the effectiveness of hunting has been limited because of safety and access to land (e.g., Weckel et al. 2011 , Williams et al. 2013 ) . -Diefenbach D et al., 2021
* Although deer management programs vary by agency, the challenge remains the same; achieving deer management goals in a manner that balanc es the values of stakeholders in a transparent manner that is defendable. - Diefenbach D et al., 2021
* In some countries, landowners have historically had significant control over management decisions for ungulates under both public and private approaches b ecause the right to shoot deer usually cannot be separated from land ownership . - Diefenbach D et al., 2021
* The fine- scale patterns present in these multidimensional data are particularly useful to predict potential population collapses and manage ecosystems accordingly (Cerini et al., 2022; Dietze et al., 2018). However, acquiring such data has traditionally involved cost- prohibitive, labour- intensive and often invasive survey methods that have consequently limited historical ecological observations both spatially and temporally (Kays et al., 2015; Pimm et al., 2015) - Besson M et al., 2022
* Some problems in particular need of study are: Nutritional requirements of deer, especially in regard to natural foods. Nutritional value of natural and planted foods, and how their abundance or depletion affects deer populations. Effect of logging intensity, distribution, and scheduling, on deer condition and population. Analysis of kill records in regard to total populations and as an index of herd and range condition. The determination of "normal" and "most productive" herd composition, i.e. age and sex ratios. Life history studies, particularly as regards herd productivity. Disease and parasite identification and control - Barick FB, 1951
* Table 2. History of Southeastern deer restoration - Barick FB, 1951
* Negative values of deer have grown in recent decades because high-density deer populations con fl ict with people through agricultural damage, deer-vehicle collisions, zoonoses, and damage to landscape plants. Balancing the positive and negative values of white-tailed deer is a daily challenge for state wildlife management agencies. - Hewitt DG, 2015
* White-tailed deer have been prominent in human cultures in North America for thousands of years, likely gaining importance after most species of mammalian megafauna went extinct during the Pleistocene, 12,000 – 15,000 years ago [ 5 ]. - Urbanek RE et al., 2011
* Public attitudes, beliefs, and interests toward deer management methods are now playing a greater role in determining which management techniques are socially acceptable, which creates challenges for deer managers (Curtis et al. 1993, Kilpatrick and Walter 1997). - Urbanek RE et al., 2011

Importance of WTD in Alabama ecology & management

Historical management practices & limitations

Existing monitoring challenges (harvest reliance, survey design)

## II. Biological Foundations

* A major limit to managing the impact of deer herds on forests in North America is that the multiple constituencies involved with deer management who do not all view the ecological role of white- tailed deer as their highest priority. 14 Whereas eco- logical damage and disease spread may be a direct function of high densities, states have not been able to reduce deer populations across a broad landscape - McShea WJ, 2012
* For white - tailed deer, changes in abundance are accomplished primarily through manipulation of the 8 harvest of female deer. Manipulation of the male population can effect change s in social behavior and sex - age structure of the population (e.g., Wallingford et al. 201 7 ) but has little effect on population trends. - Diefenbach D et al., 2021
* The fine- scale patterns present in these multidimensional data are particularly useful to predict potential population collapses and manage ecosystems accordingly (Cerini et al., 2022; Dietze et al., 2018). However, acquiring such data has traditionally involved cost- prohibitive, labour- intensive and often invasive survey methods that have consequently limited historical ecological observations both spatially and temporally (Kays et al., 2015; Pimm et al., 2015) - Besson M et al., 2022
* Our ability to reliably forecast ecosystems dynamics is limited by our capacity to understand what governs their composition, dynamics, function and structure (Dietze et al., 2018; Petchey et al., 2015) - Ellis Soto D et al., 2025
* A model is not a crystal ball; it cannot truly predict future conditions with certainty. While models can simulate possible outcomes based on specific assumptions and input data, their utility lies not in delivering accurate predictions, but in helping us explore and understand complex systems and the uncertainties within them. While models provide a structured way to explore hypotheses, test scenarios, and predict system behaviors, they rely on empirical data to ensure their accuracy and relevance. Models can guide our thinking, reveal gaps in knowledge, and structure our questions, but they cannot substitute for empirical grounding. Fieldwork remains essential for identifying, quantifying, and contextualizing uncertainties. Fieldwork provides the raw data and ecological insight needed to meaningfully construct, parameterize, and interpret models. Without the iterative feedback between observation and simulation, we risk building increasingly sophisticated models that drift further from ecological reality. Fieldwork is thus essential for any modeling work and forms the foundation of reliable models. Additionally, field ‐ based studies help validate model assumptions and outputs, ensuring that simulations reflect real ‐ world conditions. But when field effort is minimized (intentionally or otherwise), models may rely on incomplete or outdated data, thus increasing uncertainty and resulting in biased estimates, incorrect assumptions about system behavior, and poor decision ‐ making in conservation and management (Elbroch et al. 2018 ). - Ditchkoff SS & Belsare AV, 2025

Morphology, reproduction, diet, behavior, predation

Population dynamics and structure

Keystone ecological roles and ecosystem impacts

## III. Current Data Sources & Limitations

* A modification on this model is “Quality Deer Management,” which engages the public more directly in population management by encouraging relatively low deer densities through high harvest rates on females, thereby allowing males to reach older age classes un- der optimal forage conditions. 131 - McShea WJ, 2012
* Appendix 2: DEER HARVEST AND HUNTER NUMBERS IN ALABAMA FROM 1986-87 THROUGH 2001-02 - Cook C & Gray B, 2003
* However, in areas with limited mortality factors other than hunting, declining hunter participation and harvest will create significant challenges. Such challenges have existed in urban and suburban areas for decades where the effectiveness of hunting has been limited because of safety and access to land (e.g., Weckel et al. 2011 , Williams et al. 2013 ) . -Diefenbach D et al., 2021
* Season lengths and bag limits are a top - down management technique that fits with the NAM, but regulations and policy can be changed to also support bottom - up approach to deer management. For example, providing private landowners and government land management agencies with methods to increase deer harvest can address localized problems. Many states have implemented Deer Management Assistance Programs that provide landowners wit h property - specific means to increase antlerless harvests ( Table 21.2 ). Similar programs have been established to address crop damage or urban deer problems ( Table 21.2 ). The success of bottom - up approaches to deer management depends on cooperation from private landowners, as well as agency resources to administer and promote such programs, but the motivations for landowners to allow hunting are complicated. Fee - based hunt ing may work in some situations (Guynn and Schmidt 1984) but landowner attitudes towards hunting and property rights may be impediments (Wright et al. 1988, Raedeke et al. 1996). - Diefenbach D et al., 2021
* Hunters generally are not motivated by ecological concerns or deer - human conflicts because other priorities inform their motivation for hunting (Diefenbach et al. 11 1997, Holsman 2000 ). Consequently, most hunter s desire to harvest only 1 – 2 deer/year (Brown et al. 2000) , and s ome are interested in primarily harvesting antlered deer (Bhandari et al. 2006) - Diefenbach D et al., 2021
* Simply extending season lengths and bag limits will fail to control deer seasons when there a re too few hunters willing to harvest a sufficient number of antlerless deer . Also, the effectiveness of increasing seasons and bag limits is reduced when recreational hunting can not occur either because restricted access to private land or safety issues require less effective sporting arms (e.g., bows or crossbows rather than firearms) . The regulatory changes - Diefenbach D et al., 2021
* White - tailed deer populations increased throughout the 20 th century in North America , but with these increasing populations hunter participation also increased . Consequently, a successful strategy for managing deer populations wa s to regulate hunting season length (number of days of opportunity to harvest a deer) and the number of deer eac h hunter could harvest each year (bag limit). In most situations, longer seasons and a smaller bag limit could achieve the same level of harvest as a shorter season and larger bag limits. - Diefenbach D et al., 2021
* For white - tailed deer, changes in abundance are accomplished primarily through manipulation of the 8 harvest of female deer. Manipulation of the male population can effect change s in social behavior and sex - age structure of the population (e.g., Wallingford et al. 201 7 ) but has little effect on population trends. - Diefenbach D et al., 2021
* Third , within each management unit data are collected to monitor either deer abundance directly or indicators that can provide trends in deer population characteristics ( Table 21.1 ). Most states monitor harvest statistics (e.g., buck kill per unit area ; Table 2 1.1 ) and some use se x - age - kill models or accounting - type population models (Diefenbach and Shea 2011) . - Diefenbach D et al., 2021
* There are four components to any management program . First, a pplication of management actions and deer harvest and population monitoring generally occur s within defined management units. Management units can be based on political boundaries or possess ecological and social characteristics that are as homogeneous as possible within physical boundaries such as roads and rivers (Karns et al. 2016, Swihart et al. 2020). - Diefenbach D et al., 2021
* Elsewhere in the world there are different approaches to wildlife management where private landowners have greater control over the harvest of big game (Gill 1990) - Diefenbach D et al., 2021
* The fine- scale patterns present in these multidimensional data are particularly useful to predict potential population collapses and manage ecosystems accordingly (Cerini et al., 2022; Dietze et al., 2018). However, acquiring such data has traditionally involved cost- prohibitive, labour- intensive and often invasive survey methods that have consequently limited historical ecological observations both spatially and temporally (Kays et al., 2015; Pimm et al., 2015) - Besson M et al., 2022
* Nine of the eleven states reported more efficient protective legislation and law enforcement as an important requisite to restoration, and several rated this item as the most pressing need Specifically, there is need for stiffer penalties and for greater cooperation on the part of local justices in meting out penalties. There is also much room for legislation controlling stray dogs. - Barick FB, 1951
* These approaches eventually worked and in 1999, the number of antlerless deer harvested in the United States surpassed the harvest of antlered deer [ 10] - Hewitt DG, 2015
* By the 1970s deer populations in many areas were overabundant, were numerically heavily dominated by females and because of the heavy harvest of male deer, had few if any mature males. - Hewitt DG, 2015
* Our survey indicated that several state agencies lack information regarding public opinions on deer and deer management in developed areas. - Scofield CL et al., 2002

Harvest reports and hunter surveys

Existing databases and DWFF data

Strengths/weaknesses of SPR and related approaches

Notes: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

## IV. Technological & Analytical Advances

* Increasingly complex research questions and global challenges (e.g., climate change and biodiversity loss) are driving rapid development, refinement, and uses of technology in ecology. - Allan BM et al., 2018
* The fully automated monitoring frameworks that we present here integrate novel hardware and software approaches allowing the rapid generation of high resolution, multidimensional data across complex ecological communitie - Besson M et al., 2022
* By synthesising the variety of existing automated technologies and describing real- world and futurist workf lows that bring them together, we aim to stimulate such collaborations in the future— towards the development of new, user friendly and standardised pipelines that automatically monitor multiple components of multispecies systems with minimal disturbance exerted (Weinstein, 2018). - Besson M et al., 2022
* The development of fully automated frameworks may also be limited by challenges associated with building interdisciplinary collaborations among ecologists, electronic engineers and artificial intelligence specialists, to train the specialised staff needed to develop and maintain accessible automated systems (Pedroso de Lima et al., 2020). - Besson M et al., 2022
* Technologies such as automatic recorders and deep learning have not reached their full potential to support modern ecological monitoring in a fully automated manner (Hampton et al., 2013; Tuia et al., 2022) - Besson M et al., 2022
* The step change offered by such real- time data, in combination with cutting edge statistical methods such as Bayesian statistics and machine learning tools, which both leverage past state to improve predictive accuracy, offers perhaps the greatest opportunity for ecology to become a truly predictive science. - Besson M et al., 2022
* Moreover, automated methods allow the acquisition of these data in real- time, pushing ecological research from the post hoc era to one where forecasts about ecosystems fate are continually updated based on the current observed state, similar to weather forecasting (Deyle et al., 2016; Huang et al., 2019; Slingsby et al., 2020). - Besson M et al., 2022
* generated using automated frameworks (e.g. behavioural and morphological traits, abundances and distributions across multiple species) offer the opportunity to develop new predictive frameworks, which for the first FIGURE 6 Futurist examples of fully automated wildlife monitoring programs. (a) Autonomous and wireless underwater vehicle equipped with multiple high- resolution cameras and hydrophone array, together monitoring multidimensional data about coral reef communities such as habitat complexity, coral species distribution and fish functional diversity. (b) Autonomous and self- charging drones equipped with LiDAR and hyperspectral cameras for the monitoring of plant and tree f lowering phenology. 14610248, 2022, 12, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/ele.14123 by Auburn University Libraries, Wiley Online Library on [13/08/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License | 2767BESSON et al. time can synthetise data across ecological scales (from individuals to populations) and help developing novel early warning signals that precede population and community collapses (Cerini et al., 2022). - Besson M et al., 2022
* FIGURE 6 Futurist examples of fully automated wildlife monitoring programs. (a) Autonomous and wireless underwater vehicle equipped with multiple high- resolution cameras and hydrophone array, together monitoring multidimensional data about coral reef communities such as habitat complexity, coral species distribution and fish functional diversity. (b) Autonomous and self- charging drones equipped with LiDAR and hyperspectral cameras for the monitoring of plant and tree f lowering phenology. - Besson M et al., 2022
* Finally, it is important to recognise that no single machine learning method, nor computer audition/vision package can suit all automated monitoring purposes. Instead, various computational pipelines, each suited to dealing with a specific context or processing step, depending on data types and on the organisms being monitored, are likely to be need - Cook C & Gray B, 2003
* Management objectives for each goal must be defined such that they can be quantitatively evaluated by a monitoring program (Artelle et al. 2018). - Diefenbach D et al., 2021
* Effective management units should be sized to meet desired precision of a monitoring program given cost and logistical constraints. - Diefenbach D et al., 2021
* There are four components to any management program . First, a pplication of management actions and deer harvest and population monitoring generally occur s within defined management units. Management units can be based on political boundaries or possess ecological and social characteristics that are as homogeneous as possible within physical boundaries such as roads and rivers (Karns et al. 2016, Swihart et al. 2020). - Diefenbach D et al., 2021
* Leveraging participatory science for near - real time monitoring of wildlife mortality requires careful understanding of the limitations and biases of such opportunistic recordings (Taylor et al. 2024) . - Ellis Soto D et al., 2025
* In recent decades, advances in biodiversity sensors and data transmission technologies have enabled near - real time biodiversity monitoring at global scales (Besson et al. 2022) . Consequently, early detection of wildlife mortality has gained increasing attention, allowing managers to respond dynamically to short - term forecasts and shifting ecological conditions. - Logan TW et al., 2025

Remote sensing, citizen-science camera surveys, roadkill reporting

Automated monitoring technologies (machine learning, drones, sensors)

Statistical Population Reconstruction (SPR), N-mixture models, agent-based models

## V. Integrated Monitoring Alternatives

* generated using automated frameworks (e.g. behavioural and morphological traits, abundances and distributions across multiple species) offer the opportunity to develop new predictive frameworks, which for the first FIGURE 6 Futurist examples of fully automated wildlife monitoring programs. (a) Autonomous and wireless underwater vehicle equipped with multiple high- resolution cameras and hydrophone array, together monitoring multidimensional data about coral reef communities such as habitat complexity, coral species distribution and fish functional diversity. (b) Autonomous and self- charging drones equipped with LiDAR and hyperspectral cameras for the monitoring of plant and tree f lowering phenology. 14610248, 2022, 12, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/ele.14123 by Auburn University Libraries, Wiley Online Library on [13/08/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License | 2767BESSON et al. time can synthetise data across ecological scales (from individuals to populations) and help developing novel early warning signals that precede population and community collapses (Cerini et al., 2022). - Besson M et al., 2022
* Strategies to achieve management goals may be applied at the management unit scale (e.g., allocation of antlerless lice nses) or at smaller scales to address local deer - human conflicts, such as excessive crop damage or deer - vehicle collisions. - Diefenbach D et al., 2021
* The fine- scale patterns present in these multidimensional data are particularly useful to predict potential population collapses and manage ecosystems accordingly (Cerini et al., 2022; Dietze et al., 2018). However, acquiring such data has traditionally involved cost- prohibitive, labour- intensive and often invasive survey methods that have consequently limited historical ecological observations both spatially and temporally (Kays et al., 2015; Pimm et al., 2015) - Besson M et al., 2022
* In recent decades, advances in biodiversity sensors and data transmission technologies have enabled near - real time biodiversity monitoring at global scales (Besson et al. 2022) . Consequently, early detection of wildlife mortality has gained increasing attention, allowing managers to respond dynamically to short - term forecasts and shifting ecological conditions. - Logan TW et al., 2025
* The agent-based approach: 1) captures emergent phenomena; 2) provides a natural environment for the study of certain systems; and, 3) is flexible, particularly in relation to the development of geospatial models. - Castle C & Crooks A, 2006
* Krausman ( 2020 ), recognizing in the 2020s the reliance of wildlife science on models, described what he saw as some of the potential pitfalls in their use and highlighted some important considerations when using models to advance the science of wildlife management. His foundational suggestions were that (1) models should be “ developed in cooperation with wildlife managers ” , (2) modelers should utilize temporal and spatial scales that are appropriate to the data and systems being studied, and (3) the data incorporated into models should be adequate to address the issues being studied. - Ditchkoff SS & Belsare AV, 2025

Double-sampling approaches (broad + intensive)

Merging multiple data sources (citizen science + harvest + localized data)

Evaluations of feasibility, cost, and scale

## VI. Modeling Approaches & Decision Frameworks

* Most important variables and importance value (if ≥50) for random forests and extreme gradient boosting (egb) models of deer densities (low- density class < 5.8 deer/km2, moderately low to high- density class ≥5.8 deer/km2, low and moderately low- density class <11.6 deer/km2, and moderately high and high- density class ≥11.6 deer/km2) by region - Hanberry BB, 2021
* Wildlife man- agers and researchers have noted that the model has problems with expanding use of its revenues and ef- fort beyond game species, developing a strong role for the nonhunting citizen, and replacing an ag- ing constituency of hunters. 132 , 133 These socioeco- nomic changes, and safety concerns, result in in- creasing portions of private land in exurbia being closed to hunting either by individual landowners or homeowner associations. 134 - McShea WJ, 2012
* The North American model has been credited with expanding game populations in North America and creating a system of forest land that is accessible to the public. 13 - McShea WJ, 2012
* A modification on this model is “Quality Deer Management,” which engages the public more directly in population management by encouraging relatively low deer densities through high harvest rates on females, thereby allowing males to reach older age classes un- der optimal forage conditions. 131 - McShea WJ, 2012
* Two issues hin- der the ability of managers to achieve their goals. First, the current wildlife management system (i.e., the North American model) was developed to grow wildlife populations and may not have enough in- centives to meet the current challenges of reducing deer populations. Second, state wildlife managers have adopted a paradigm of cultural carry capac- ity for setting population levels, and this qualitative measure does not insure densities below biological carry capacity. - McShea WJ, 2012
* Moreover, automated methods allow the acquisition of these data in real- time, pushing ecological research from the post hoc era to one where forecasts about ecosystems fate are continually updated based on the current observed state, similar to weather forecasting (Deyle et al., 2016; Huang et al., 2019; Slingsby et al., 2020). - Besson M et al., 2022
* Third , within each management unit data are collected to monitor either deer abundance directly or indicators that can provide trends in deer population characteristics ( Table 21.1 ). Most states monitor harvest statistics (e.g., buck kill per unit area ; Table 2 1.1 ) and some use se x - age - kill models or accounting - type population models (Diefenbach and Shea 2011) . - Diefenbach D et al., 2021
* In North America, wildlife is held in the public trust and hunting is regulated by government agencies rather than by landowners . This approach to wildlife management has been termed the North American Model for Wildlife Conservation (NAM) , in which hunting and hunters are considered the foundation for wildlife conservation and provide the bulk of conservation funding (Heffelfinger et al. 2013) - Besson M et al., 2022
* Our ability to reliably forecast ecosystems dynamics is limited by our capacity to understand what governs their composition, dynamics, function and structure (Dietze et al., 2018; Petchey et al., 2015) - Ellis Soto D et al., 2025
* In recent decades, advances in biodiversity sensors and data transmission technologies have enabled near - real time biodiversity monitoring at global scales (Besson et al. 2022) . Consequently, early detection of wildlife mortality has gained increasing attention, allowing managers to respond dynamically to short - term forecasts and shifting ecological conditions. - Logan TW et al., 2025
* Varying degrees of accuracy and completeness in the model inputs determine whether the output should be used purely for qualitative insight, or accurate quantitative forecastin - Castle C & Crooks A, 2006
* Finally, the agent-based approach to modelling is flexible, particularly in relation to geospatial modelling. Notably, spatial simulations benefit from the mobility that agent-based models offer. To reiterate, an agent-based model can be defined within any given system environment (e.g. a building, a city, a road network, a computer network, etc). Furthermore, agents have the ability to physically move within their environment, in different directions and at different velocities - Castle C & Crooks A, 2006
* The agent-based approach: 1) captures emergent phenomena; 2) provides a natural environment for the study of certain systems; and, 3) is flexible, particularly in relation to the development of geospatial models. - Castle C & Crooks A, 2006
* Agent-based models are comprised of multiple, interacting agents situated within a model or simulation environment. A relationship between agents is specified, linking agents to other agents and / or other entities within a system. Relationships may be specified in a variety of ways, from simply reactive (i.e. agents only perform actions when triggered to do so by some external stimulus e.g. actions of another agent), to goal-directed (i.e. seeking a particular goal). The behaviour of agents can be scheduled to take place synchronously (i.e. every agent performs actions at each discrete time step), or asynchronously (i.e. agent actions are scheduled by the actions of other agents, and / or with reference to a clock). - Xie J et al., 1999
* In this study, we tried to balance model simplicity, accuracy, and generality in order to be accessible to the wildlife management community (Levins, 1966). - Xie J et al., 1999
* Fig. 1. Part of the user interface in DeerMOM showing the five sectors. - Xie J et al., 1999
* We developed a hybrid (mechanistic and empirical) model, the deer management options model (DeerMOM), to evaluate the effects of deer management options on population size, sex and age structure. - Xie J et al., 1999
* A model is not a crystal ball; it cannot truly predict future conditions with certainty. While models can simulate possible outcomes based on specific assumptions and input data, their utility lies not in delivering accurate predictions, but in helping us explore and understand complex systems and the uncertainties within them. While models provide a structured way to explore hypotheses, test scenarios, and predict system behaviors, they rely on empirical data to ensure their accuracy and relevance. Models can guide our thinking, reveal gaps in knowledge, and structure our questions, but they cannot substitute for empirical grounding. Fieldwork remains essential for identifying, quantifying, and contextualizing uncertainties. Fieldwork provides the raw data and ecological insight needed to meaningfully construct, parameterize, and interpret models. Without the iterative feedback between observation and simulation, we risk building increasingly sophisticated models that drift further from ecological reality. Fieldwork is thus essential for any modeling work and forms the foundation of reliable models. Additionally, field ‐ based studies help validate model assumptions and outputs, ensuring that simulations reflect real ‐ world conditions. But when field effort is minimized (intentionally or otherwise), models may rely on incomplete or outdated data, thus increasing uncertainty and resulting in biased estimates, incorrect assumptions about system behavior, and poor decision ‐ making in conservation and management (Elbroch et al. 2018 ). - Ditchkoff SS & Belsare AV, 2025
* With this being the case, how can we expect our managers to successfully utilize, or trust, the models we develop? Of greater import, how can we expect our managers to effectively communicate about the models and their predictions with decision ‐ makers (legislators, conservation advisory boards, etc.), the press, or the public? If the manager doesn't understand the model, how can they sell its output to our stakeholders and/or decision ‐ makers? - Ditchkoff SS & Belsare AV, 2025
* Their development and implementation require advanced training, which often far exceeds the training of our front ‐ line biologists. With this being the case, how can we expect our managers to successfully utilize, or trust, the models we develop? - Ditchkoff SS & Belsare AV, 2025
* Take N ‐ mixture models (Royle 2004 ) using camera traps for white ‐ tailed deer as an example (Keever et al. 2017 ). N ‐ mixture models incorporate images that do not contain any deer as data in the model. A manager once asked us, “ How is it possible that an image of no deer can be used to generate population estimates? ” Because the mathematics of the model were beyond the comprehension of the user, we simply said, “ Trust us. ” This is not a good recipe for management success. - Ditchkoff SS & Belsare AV, 2025
* Our models are becoming opaque black boxes that we expect the user to employ blindly and based simply on faith in the developer. - Ditchkoff SS & Belsare AV, 2025
* Krausman ( 2020 ), recognizing in the 2020s the reliance of wildlife science on models, described what he saw as some of the potential pitfalls in their use and highlighted some important considerations when using models to advance the science of wildlife management. His foundational suggestions were that (1) models should be “ developed in cooperation with wildlife managers ” , (2) modelers should utilize temporal and spatial scales that are appropriate to the data and systems being studied, and (3) the data incorporated into models should be adequate to address the issues being studied. - Ditchkoff SS & Belsare AV, 2025
* Models have become an integral component of wildlife conservation and management, and lie at the foundation of decision ‐ making in our field today. - Barick FB, 1951
* Clearly the unregulated market and subsistence hunting of the 1800s was the antithesis of conservation for white-tailed deer and many other wildlife species. The genius of conservation in contemporary North America is its explicit link to hunting, a link that paradoxically arose out of the near extermination of many wildlife species in the 1800s [ 35 ]. This system, called the North American Model of Wildlife Conservation, relies on the self-interest of sport hunters to allocate wildlife to legitimate purposes through legislation and regulation and to fund much of the continent ’ s wildlife conservation activities. Under this model, hunters have been the engine behind the conservation, management, and research of white-tailed deer, the most important big game animal in North America. - Hewitt DG, 2015

General WTD biological model

Alternative modeling frameworks (matrix vs. ABMs)

Decision-analysis scenarios

Model validation and trade-off evaluation

## VII. Human Dimensions & Stakeholder Needs

* In the United States, wildlife does not belong to the landowner, but the citizen, and in most states the landowner cannot restrict the movement of wildlife across their land. - McShea WJ, 2012
* Wildlife man- agers and researchers have noted that the model has problems with expanding use of its revenues and ef- fort beyond game species, developing a strong role for the nonhunting citizen, and replacing an ag- ing constituency of hunters. 132 , 133 These socioeco- nomic changes, and safety concerns, result in in- creasing portions of private land in exurbia being closed to hunting either by individual landowners or homeowner associations. 134 - McShea WJ, 2012
* The North American model has been credited with expanding game populations in North America and creating a system of forest land that is accessible to the public. 13 - McShea WJ, 2012
* A modification on this model is “Quality Deer Management,” which engages the public more directly in population management by encouraging relatively low deer densities through high harvest rates on females, thereby allowing males to reach older age classes un- der optimal forage conditions. 131 - McShea WJ, 2012
* Adoption of a management plan based on biological carrying capacity relies on cross-agency cooperation and buy-in by stakeholder groups, which includes the continued support of the citizen hunter and by gaining the support of other conservationists - McShea WJ, 2012
* As opposed to most species in the eastern forests, expertise, manpower, and bureaucracy are in place to manage deer populations across its range. With doi: 10.1111/j.1749-6632.2011.06376.x Ann. N.Y. Acad. Sci. 1249 (2012) 45–56 c © 2012 New York Academy of Sciences. 45 Deer and eastern forests McShea white-tailed deer, there is a dedicated management structure at all levels of government that can en- act recommendations based on a public mandate - Besson M et al., 2022
* We note that societal interest in how domestic animals are raised and processed has increased interest in wild game as a source of protei n and this interest has, in part, increased hunting participation by non - traditional hunters, especially women (Pollan 2006). In addition, many state agencies are engaged in efforts to recruit and retain hunters (Price Tack et al. 2018). However , we identi fied declining trends in hunter numbers as a n important factor that will determine the future and importance of deer hunting to achieve social, ecological, and disease - related management objectives. - Diefenbach D et al., 2021
* Recreational de er hunting will continue to have a role in deer management , but it may transition from the primary method to one of many alternatives. The magnitude of hunting’s contribution to the wildlife manager’s toolbox will likely be determined by future hunter participation , as well as hunter and general public acceptance of changes in regulations or management actions . - Diefenbach D et al., 2021
* Season lengths and bag limits are a top - down management technique that fits with the NAM, but regulations and policy can be changed to also support bottom - up approach to deer management. For example, providing private landowners and government land management agencies with methods to increase deer harvest can address localized problems. Many states have implemented Deer Management Assistance Programs that provide landowners wit h property - specific means to increase antlerless harvests ( Table 21.2 ). Similar programs have been established to address crop damage or urban deer problems ( Table 21.2 ). The success of bottom - up approaches to deer management depends on cooperation from private landowners, as well as agency resources to administer and promote such programs, but the motivations for landowners to allow hunting are complicated. Fee - based hunt ing may work in some situations (Guynn and Schmidt 1984) but landowner attitudes towards hunting and property rights may be impediments (Wright et al. 1988, Raedeke et al. 1996). - Diefenbach D et al., 2021
* Although deer management programs vary by agency, the challenge remains the same; achieving deer management goals in a manner that balanc es the values of stakeholders in a transparent manner that is defendable. - Diefenbach D et al., 2021
* For white - tailed deer, changes in abundance are accomplished primarily through manipulation of the 8 harvest of female deer. Manipulation of the male population can effect change s in social behavior and sex - age structure of the population (e.g., Wallingford et al. 201 7 ) but has little effect on population trends. - Diefenbach D et al., 2021
* In addition to deer abundance, other data may be collected to assess how well objectives are being achieved, such as stakeholder opinions ( Curtis and Hauber 1997 ) and habitat conditions ( Rosenberry et al. 2009 ). - Diefenbach D et al., 2021
* Second, management goals and objectives must be developed for each management unit that represent public values within the context of the wildlife agency’s mission and legal authority. - Diefenbach D et al., 2021
* There are four components to any management program . First, a pplication of management actions and deer harvest and population monitoring generally occur s within defined management units. Management units can be based on political boundaries or possess ecological and social characteristics that are as homogeneous as possible within physical boundaries such as roads and rivers (Karns et al. 2016, Swihart et al. 2020). - Diefenbach D et al., 2021
* Management of white - tailed deer in North America is a top - down process by which wildlife agencies develop a management plan with input from the public , agency staffs monitor the deer population, and then agency staffs make recommendations to decision maker s regarding hunting regulations to meet established goals. - Diefenbach D et al., 2021
* In some countries, landowners have historically had significant control over management decisions for ungulates under both public and private approaches b ecause the right to shoot deer usually cannot be separated from land ownership . - Diefenbach D et al., 2021
* Elsewhere in the world there are different approaches to wildlife management where private landowners have greater control over the harvest of big game (Gill 1990) - Diefenbach D et al., 2021
* In North America, wildlife is held in the public trust and hunting is regulated by government agencies rather than by landowners . This approach to wildlife management has been termed the North American Model for Wildlife Conservation (NAM) , in which hunting and hunters are considered the foundation for wildlife conservation and provide the bulk of conservation funding (Heffelfinger et al. 2013) - Besson M et al., 2022
* date, participatory science platforms provide the m ajority of biodiversity data collected worldwide (Callaghan et al. 2023) in a manner that is cost - effective, taxonomically expansive (Chandler et al. 2017) , and accessible across public and private lands - Ellis Soto D et al., 2025
* The rapid increase in participatory science (also known as “citizen or community science”) offers a promising angle to support existing efforts that monitor wildlife mortality (Supplementary Figure 1). - Ellis Soto D et al., 2025
* ment methods, are variable across socio-economic categories, such as between developed and developing countries ( Dickman, 2010 ), and rural and urban environments ( Kansky et al., 2016 ). To develop cocreated solutions, the variety of social tolerances needs to be clearly communicated ( Olsen, 2022 ) in order to enable equitable discussion ( White and Ward, 2010 ). Social elicitation methods can be used to facilitate those discussions, - Scofield CL et al., 2002
* Given the conflicting interests surrounding deer, it is essential to establish management goals that consider the needs and requirements of different stakeholders as well as the integrity of the ecosystem. - Enck J et al., 2003
* Many factors affecting recruitment and retention ofnew hunters result from macro socioeconomic (e.g.,economic, social and cultural) phenomena that are mostly outside the purview of traditional wildlife managementactivities (Dann & Peyton, 1996). - Enck J et al., 2003
* With this being the case, how can we expect our managers to successfully utilize, or trust, the models we develop? Of greater import, how can we expect our managers to effectively communicate about the models and their predictions with decision ‐ makers (legislators, conservation advisory boards, etc.), the press, or the public? If the manager doesn't understand the model, how can they sell its output to our stakeholders and/or decision ‐ makers? - Ditchkoff SS & Belsare AV, 2025
* Other items listed were: more intensive club participation in restoration work, additional sources of deer for restocking, increased trapping efficiency, education of commissioners in regard to biological factors, more money, and improved landowner-sportsmen relations. - Barick FB, 1951
* In most states, lack of management is due to safety concerns, conflicting social attitudes and perceptions about deer, hunting and firearm-discharge restrictions, and liability or public relations concerns (DeNicola et al. 2000). - Urbanek RE et al., 2011
* Human– deer conflicts such as deer–vehicle collisions and damage to personal property are escalating in many metropolitan areas throughout the nation, and management of overabundant deer populations has become a common concern of citizens (Cornicelli 1992, McAninch 1995, Conover 1997, West and Parkhurst 2002, Hubbard and Nielsen 2009 - Urbanek RE et al., 2011
* Although deer management is a frequently debated topic, wildlife biologists must have reliable information concerning human attitudes toward deer management to properly manage deer in developed areas (Storm et al. 2007). - Urbanek RE et al., 2011
* Public attitudes, beliefs, and interests toward deer management methods are now playing a greater role in determining which management techniques are socially acceptable, which creates challenges for deer managers (Curtis et al. 1993, Kilpatrick and Walter 1997). - Urbanek RE et al., 2011
* Our survey indicated that several state agencies lack information regarding public opinions on deer and deer management in developed areas. - Scofield CL et al., 2002

Stakeholder values and management expectations

Public attitudes and acceptance

Policy implications for harvest and monitoring

## VIII. Literature Gaps & Future Directions

* By synthesising the variety of existing automated technologies and describing real- world and futurist workf lows that bring them together, we aim to stimulate such collaborations in the future— towards the development of new, user friendly and standardised pipelines that automatically monitor multiple components of multispecies systems with minimal disturbance exerted (Weinstein, 2018). - Besson M et al., 2022
* The step change offered by such real- time data, in combination with cutting edge statistical methods such as Bayesian statistics and machine learning tools, which both leverage past state to improve predictive accuracy, offers perhaps the greatest opportunity for ecology to become a truly predictive science. - Besson M et al., 2022
* generated using automated frameworks (e.g. behavioural and morphological traits, abundances and distributions across multiple species) offer the opportunity to develop new predictive frameworks, which for the first FIGURE 6 Futurist examples of fully automated wildlife monitoring programs. (a) Autonomous and wireless underwater vehicle equipped with multiple high- resolution cameras and hydrophone array, together monitoring multidimensional data about coral reef communities such as habitat complexity, coral species distribution and fish functional diversity. (b) Autonomous and self- charging drones equipped with LiDAR and hyperspectral cameras for the monitoring of plant and tree f lowering phenology. 14610248, 2022, 12, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/ele.14123 by Auburn University Libraries, Wiley Online Library on [13/08/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License | 2767BESSON et al. time can synthetise data across ecological scales (from individuals to populations) and help developing novel early warning signals that precede population and community collapses (Cerini et al., 2022). - Besson M et al., 2022
* We note that societal interest in how domestic animals are raised and processed has increased interest in wild game as a source of protei n and this interest has, in part, increased hunting participation by non - traditional hunters, especially women (Pollan 2006). In addition, many state agencies are engaged in efforts to recruit and retain hunters (Price Tack et al. 2018). However , we identi fied declining trends in hunter numbers as a n important factor that will determine the future and importance of deer hunting to achieve social, ecological, and disease - related management objectives. - Diefenbach D et al., 2021
* Recreational de er hunting will continue to have a role in deer management , but it may transition from the primary method to one of many alternatives. The magnitude of hunting’s contribution to the wildlife manager’s toolbox will likely be determined by future hunter participation , as well as hunter and general public acceptance of changes in regulations or management actions . - Diefenbach D et al., 2021
* We envision in the future that multiple methods will be required to control deer populations that likely will require an adaptive management approach (Nielsen et al. 1997 ). - Diefenbach D et al., 2021
* White - tailed deer populations increased throughout the 20 th century in North America , but with these increasing populations hunter participation also increased . Consequently, a successful strategy for managing deer populations wa s to regulate hunting season length (number of days of opportunity to harvest a deer) and the number of deer eac h hunter could harvest each year (bag limit). In most situations, longer seasons and a smaller bag limit could achieve the same level of harvest as a shorter season and larger bag limits. - Diefenbach D et al., 2021
* The future chall enge to manag ing ungulate populations to meet objectives is likely to become more difficult as participation in recreational hunting declines and ungulate populations become more abundant - Diefenbach D et al., 2021
* Maximizing recreational opportunity, either for consumptive or non - consumptive purposes, can be in direct confli ct with human - conflict and ecological objectives. - Diefenbach D et al., 2021
* Leveraging participatory science for near - real time monitoring of wildlife mortality requires careful understanding of the limitations and biases of such opportunistic recordings (Taylor et al. 2024) . - Ellis Soto D et al., 2025
* A model is not a crystal ball; it cannot truly predict future conditions with certainty. While models can simulate possible outcomes based on specific assumptions and input data, their utility lies not in delivering accurate predictions, but in helping us explore and understand complex systems and the uncertainties within them. While models provide a structured way to explore hypotheses, test scenarios, and predict system behaviors, they rely on empirical data to ensure their accuracy and relevance. Models can guide our thinking, reveal gaps in knowledge, and structure our questions, but they cannot substitute for empirical grounding. Fieldwork remains essential for identifying, quantifying, and contextualizing uncertainties. Fieldwork provides the raw data and ecological insight needed to meaningfully construct, parameterize, and interpret models. Without the iterative feedback between observation and simulation, we risk building increasingly sophisticated models that drift further from ecological reality. Fieldwork is thus essential for any modeling work and forms the foundation of reliable models. Additionally, field ‐ based studies help validate model assumptions and outputs, ensuring that simulations reflect real ‐ world conditions. But when field effort is minimized (intentionally or otherwise), models may rely on incomplete or outdated data, thus increasing uncertainty and resulting in biased estimates, incorrect assumptions about system behavior, and poor decision ‐ making in conservation and management (Elbroch et al. 2018 ). - Ditchkoff SS & Belsare AV, 2025

Data deficiencies (precision, bias, logistical feasibility)

Opportunities for integration of new technologies

Recommendations for standardized harvest/monitoring data collection

## IX. Deliverables & Implications for Management

Conceptual Map Depicting the Complexity of Contemporary Management Challenges

|  |  |  |
| --- | --- | --- |
| **Item** | **Logic** | **References** |
| Deer Population | Central to all management issues: fluctuations from collapse → recovery → overabundance. | adams1960; trefethen1970; hanberry2020; acevedocharry2025; berl2025; cook2003; hewitt2015; mcshea2012 |
| Hunter Participation | Linked to cultural values, agency funding, and deer population control. Declining numbers reduce harvest efficiency and weaken agency revenue. | enck2003; diefenbach2021; hewitt2015; urbanek2011 |
| Profit & Funding (Financial Foundations) | Wildlife agencies depend on hunter-derived funds (licenses, Pittman–Robertson). Declining hunters threaten fiscal sustainability. | mcshea2012; cook2003; hewitt2015; diefenbach2021 |
| State Agencies | Regulate harvest, set goals, and mediate between science and stakeholders. Effectiveness constrained by funding and shifting public trust. | diefenbach2021; logan2025; urbanek2011 |
| Regulations | Historically framed by the North American Model (NAM). Inadequate for addressing overabundance, suburban deer, and disease. | hewitt2015; mcshea2012; diefenbach2021; hanberry2020 |
| Disease | High deer densities linked to CWD, EHD, TB. Disease undermines hunter confidence, public perception, and agency credibility. | agusto2025; needham2007; mcshea2012; belsare1970b; ditchkoff2025 |
| Public Health | Zoonotic risks such as Lyme disease and tick vectors tied to deer abundance. Expanding deer–human contact increases zoonotic and safety issues. | scofield2002; white2010; schwegmann2024; diefenbach2021 |
| Public Perception and Trust | Trust in science and agencies is mediated by management outcomes and transparency. Distrust hinders cooperation in adaptive strategies. | logan2025; ditchkoff2025; urbanek2011; allan2018 |
| Traditional Values and Beliefs | Hunting traditions sustain NAM but are eroding with cultural change, creating disconnects with modern realities. | hewitt2015; urbanek2011; brown1970; scofield2002 |
| Climate Change | Alters range limits, forage availability, and population dynamics; synergistic with disease spread and public health risks. | dawe2016; cote2004; bakshi2024; schwegmann2024 |
| Urbanization | Suburban sprawl limits hunting access and magnifies conflicts (vehicle collisions, property damage). | scofield2002; urbanek2011; conover1995; hubbard2009 |
| Competition | Interactions with elk, moose, and other cervids (competition; shared disease pools). | schwegmann2024; cote2004; fuller2001a |
| Captive Populations | Farming and captive cervids increase CWD transmission risks and regulatory complexity. | mcshea2012; needham2007; belsare1970b |
| Crossroad | Management decisions to address challenges of the 21st century requires advanced management, monitoring, and modeling approaches | diefenbach2021; ditchkoff2025; logan2025; brandell2022; allan2018 |

A diagram of a problem

AI-generated content may be incorrect.

S1 - D:B = 5:1

S2 - D:B = 3/1

S3: Harvest Dates

S4: Harvest Length