White-tailed Deer Management in the 21st Century

## Introduction

White-tailed deer (*Odocoileus virginianus*) have long been a focal species in North American wildlife management, valued for their ecological, cultural, and economic importance (**hewitt2015?**; **enck2003?**). Their recovery from near-extirpation in the early 20th century—driven by restocking programs, regulatory reforms, and the development of the North American Model of Wildlife Conservation—remains one of the most celebrated conservation achievements (**hanberry2020?**; **barick1951?**; **halls1984?**; **mccullough1979?**). This model, which designates wildlife as a public trust resource and legitimizes regulated hunting as a management tool, has guided policy and practice for more than a century (**hewitt2015?**; **miller1995?**). However, the ecological, social, and political context of deer management in the 21st century presents novel challenges that differ markedly from those of the past (**game2014?**; **ditchkoff2025?**).

Emerging infectious diseases pose some of the most pressing threats to deer populations and management objectives. Chronic wasting disease (CWD), epizootic hemorrhagic disease (EHD), bovine viral diarrhea virus (BVDV), and meningeal worm can cause substantial mortality, reduce recruitment, and alter population dynamics (**belsare2020?**; **passler2008?**; **passler2009?**; **mysterud2021?**). The spread and persistence of these pathogens are influenced by environmental change, captive cervid operations, and anthropogenic translocations (**belsare2020?**; **brandell2022?**). Surveillance and control efforts are frequently hindered by biased sampling, resource limitations, and sociopolitical resistance to management interventions (**brandell2022?**; **game2014?**).

Climate change is further reshaping the distribution, behavior, and health of deer populations (**bakshi2024?**; **hanberry2019?**). Northward range expansion into historically deer-free areas such as Alaska has introduced novel ecological interactions, altered predator–prey dynamics, and increased the potential for pathogen emergence in naïve ecosystems (**hanberry2019?**; **boucher2025?**). In many regions, these changes occur against a backdrop of stakeholder skepticism toward climate science, creating tension between agency priorities and constituent values (**kansky2025?**).

Socioeconomic factors compound these ecological challenges. Declining hunter participation—a trend driven by demographic shifts, competing recreational opportunities, and changing cultural attitudes—threatens the primary funding mechanism for state wildlife agencies through hunting license sales and Pittman–Robertson excise taxes (**enck2003?**; **nda2025?**). Distrust in government institutions and science denial among some stakeholder groups can erode compliance with regulations and support for management actions (**urbanek2011?**; **scofield2002?**). In some cases, political or economic pressures may disincentivize disease surveillance or reporting if such findings could reduce hunter engagement and agency revenue (**draper2025?**).

Management strategies vary widely among jurisdictions, reflecting differences in ecological conditions, disease prevalence, and sociopolitical context (**missouridmp2025?**; **minnesotadmp2018?**; **wiskirchen2023?**). Programs such as Deer Management Assistance Programs (DMAP) can improve landowner–agency collaboration but also generate conflict where objectives diverge (**pruitt2023?**; **wiskirchen2023?**). The increasing overlap of deer with agricultural lands, urban areas, and mixed-ownership landscapes further complicates management by introducing diverse and sometimes competing stakeholder priorities (**tack2017?**; **forsyth2022?**).

Accurate and defensible population assessment is foundational to deer management. Historically, agencies have relied on approaches such as Sex-Age-Kill (SAK), Simple Population Reconstruction (SPR), and matrix-based models (**caswell2014?**; **norton2015?**). While these methods are operationally straightforward, they often depend on restrictive assumptions, lack flexibility, and may not capture the stochasticity, spatial heterogeneity, or behavioral complexity of deer populations (**forsyth2022?**; **brandell2022?**). Advances in ecological modeling—particularly Bayesian state-space models, integrated population models (IPMs), and agent-based models (ABMs)—offer more robust ways to incorporate uncertainty, combine disparate data sources, and simulate individual-level processes (**schaub2007?**; **plard2019?**; **belsare2020?**; **nagyreis2021?**). However, these methods require greater computational resources, technical expertise, and often extensive datasets (**cegielski2016?**; **robinson2016?**).

Technological innovation is expanding the scope and scale of data collection. Telemetry devices have become lighter, more accurate, and less invasive (**saalfeld2007?**; **jackson2013?**); camera traps paired with artificial intelligence are streamlining species detection and classification (**beery2019?**; **pricetack2016?**; **mulero2025?**); and unmanned aerial systems are providing novel perspectives on distribution and abundance (**lyu2024?**). Cloud-based platforms and open-source software such as R, GitHub, NetLogo, and Shiny, as well as field-data applications like ArcGIS Field Maps and Survey123, are facilitating real-time monitoring, collaborative modeling, and reproducible workflows (**jones2024?**; **forsyth2022?**). Despite these advances, barriers remain in standardizing protocols, ensuring reproducibility, and making tools accessible to diverse agencies with varying resources (**forsyth2022?**; **brandell2022?**).

Given the multifaceted challenges of the 21st century, reliance on a single modeling framework is increasingly inadequate for supporting adaptive management. A pluralistic approach that integrates multiple modeling tools—each contributing unique strengths—can improve inference, highlight uncertainty, and increase the transparency and defensibility of management decisions (**starfield1997?**; **robinson2016?**). This “toolbox” perspective, akin to Ani’s “Rule of 3,” emphasizes the value of modular frameworks capable of addressing diverse management contexts while remaining adaptable to new data and changing conditions.

By situating current deer management within its historical context and integrating ecological, technological, and sociopolitical dimensions, this synthesis underscores the urgent need for adaptive, data-driven, and stakeholder-inclusive strategies to sustain white-tailed deer populations in an era of unprecedented change.

## Manuscript Structure

### Historical Context of White-tailed Deer Management

* Near-extirpation in early 20th century and recovery through restocking programs (Hanberry and Hanberry 2020; Barick 1951; Halls 1984; McCullough 1979).
* Establishment of the North American Model of Wildlife Conservation (Hewitt 2015; Enck et al. 2003).
* Legislation such as the Pittman–Robertson Act and state-level policy changes (Brown et al. 2000; Hewitt 2015).
* Cultural significance of hunting traditions (Tack 2017; Urbanek et al. 2011).

### Emerging and Evolving Challenges

* Spread of diseases including CWD, EHD, BVDV, and meningeal worm (Belsare et al. 2020; Passler et al. 2008, 2009; Mysterud et al. 2021).
* Impacts of climate change on distribution and habitat suitability (Bakshi et al. 2024; Hanberry and Hanberry 2019; Boucher et al. 2025).
* Stakeholder resistance to science-based recommendations (Game et al. 2014; Kansky et al. 2025).
* Funding declines due to reduced hunter participation (Enck et al. 2003; NDA Deer Report 2025).

### Regional Variability in Management Strategies

* Differences in harvest regulations and surveillance protocols (Brandell et al. 2022; Draper et al. 2025).
* Case studies: Missouri DMP, Minnesota DMP, and Southeastern DMAP programs (Missouri DMP 2025; Minnesota DMP 2018; Wiskirchen et al. 2023).
* Conflicts between private landowners and public agencies (Pruitt et al. 2023; Wiskirchen et al. 2023).

### Population Modeling Approaches

* Traditional methods: SAK, SPR, and matrix-based models (Caswell 2014; Norton 2015).
* Modern approaches: Bayesian state-space models, IPMs, and ABMs (Schaub et al. 2007; Plard et al. 2019; Belsare et al. 2020).
* Comparative evaluation of assumptions, data needs, and adaptability (Forsyth et al. 2022; Brandell et al. 2022).

### Technological Advances in Monitoring and Modeling

* Telemetry improvements in collar size, weight, and precision (Saalfeld and Ditchkoff 2007; Jackson and Ditchkoff 2013).
* Integration of camera traps with AI and machine learning (Beery et al. 2019; Price Tack et al. 2016; Mulero-Pázmány et al. 2025).
* Use of drones for thermal imaging surveys (Lyu et al. 2024).
* Adoption of cloud-based tools for real-time data collection (Jones 2024; Forsyth et al. 2022).

### Integrating Sociopolitical Considerations

* Impact of hunter demographics on funding and policy (Enck et al. 2003; NDA Deer Report 2025).
* Trust-building between agencies and stakeholders (Urbanek et al. 2011; Scofield et al. 2002).
* Addressing science denial and misinformation (Game et al. 2014; Kansky et al. 2025).

### Proposed Pluralistic Framework for Decision-making

* Ani’s ‘Rule of 3’ for using multiple models (Starfield 1997; Robinson et al. 2016).
* Modular, adaptable, and transparent framework design (Robinson et al. 2016; Forsyth et al. 2022).
* Application in adaptive management contexts (Nagy-Reis et al. 2021; Belsare et al. 2020).

### Case Studies and Regional Applications

* Application of pluralistic framework in high-CWD prevalence regions (Belsare et al. 2020; Brandell et al. 2022).
* Integration of disease surveillance with harvest data (Brandell et al. 2022; Norton 2015).
* Stakeholder-inclusive decision processes (Pruitt et al. 2023; Wiskirchen et al. 2023).

### Management Implications and Recommendations

* Strategies for enhancing disease detection and response (Belsare et al. 2020; Brandell et al. 2022).
* Improving adaptability of harvest regulations (Forsyth et al. 2022; Draper et al. 2025).
* Investing in technological capacity and training (Forsyth et al. 2022; Jones 2024).

### Future Research Directions

* Long-term monitoring of climate change impacts (Bakshi et al. 2024; Hanberry and Hanberry 2019).
* Exploring socio-economic drivers of management participation (Enck et al. 2003; Kansky et al. 2025).
* Developing scalable and accessible modeling tools (Jones 2024; Robinson et al. 2016).

### Conclusions

* Synthesis of key findings (Hanberry and Hanberry 2020; Forsyth et al. 2022).
* Reaffirming the need for adaptive, data-driven, and inclusive management (Starfield 1997; Robinson et al. 2016).