EVALUATION OF EXPANDABLE GPS COLLARS FOR WHITE-TAILED DEER FAWNS AND PREFERENCES OF CAPTIVE WHITE-TAILED DEER FOR ACORN SPECIES OF THE SOUTHEASTERN U.S.

by

ZACHARY GAGE WESNER

(Under the Direction of Gino J. D'Angelo)

ABSTRACT

Behavioral studies using captive animals offer certain advantages compared to field observations by allowing for more detailed evaluations, controlling for extraneous variables, and ensuring animal welfare. Integrating Global Positioning System (GPS) technology with expandable collars will allow researchers to more accurately investigate survival of white-tailed deer (*Odocoileus virginianus*) fawns. I tested fit and function of GPS collars on fawns and conducted behavioral observations at Whitehall Deer Research Facility, Athens, GA, USA. Fawns with GPS collars were less vigilant, slept more, and retained collars for a mean 181 (±85 [SD]) days. Preferential consumption of oak (*Quercus* spp.) acorns by deer could affect oak regeneration in the southeastern United States. I conducted feeding preference trials with captive deer to evaluate their selection for 7 species of acorns native to the southeastern United States. Deer preferred acorns of the white oak group compared to acorns of the red oak group.

INDEX WORDS: acorns, behavior, expandable GPS collar, fawns, food preferences, nutrition, oaks, *Odocoileus virginianus*, *Quercus* spp., white-tailed deer

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Behavioral studies using captive animals offer certain advantages when designing and conducting research compared to field studies using wild animals (Jayne and See 2015). Field observations of animal behavior can be problematic as observers may be unable to accurately record data from a distance (Dostaler et al. 2011). Moving too close to wild animals may impact their behavior, ultimately biasing evaluations. Additionally, focal animals may frequently move out of view during observations, making it impossible to collect data at times. Assessing behavior of animals in captive settings can allow for more detailed observations of animals, minimize human influence on behavior, and help control for extraneous variables (e.g., weather, noise, and timing of data collection; Scott and Provenza 2000, Dostaler et al. 2011, Jayne and See 2015). Captive studies also allow researchers to closely monitor animal welfare (e.g., indicators of stress, changes in behavior, signs of illness or injury, and intake of food and water) throughout a study's duration (Swaisgood 2006, Jayne and See 2015).

GPS Fawn Collars

Fawn survival and recruitment are important vital rates influencing growth of white-tailed deer (*Odocoileus virginianus*) populations (Chitwood et al. 2015, Gulsby et al. 2015, Gingery et al. 2018). Developing an understanding of how vital rates impact population dynamics of deer is especially important when managing declining populations (Chitwood et al.

2015). Quality estimates of these parameters are difficult to obtain by relying on traditional telemetry methods (i.e., radio-telemetry using very high frequency [VHF] transmitters; Bowman et al. 2000, Rodgers 2001) because the frequency, accuracy, and precision of fix locations are limited (Pusateri-Burroughs et al. 2006, Cherry et al. 2014). Additionally, inevitable disturbances associated with data collection (i.e., influencing behavior of fawns, their dams, or predators) may present unintended biases.

Previous studies evaluating fawn survival and recruitment used VHF transmitters attached to expandable collar designs. These collars are constructed to accommodate the neck growth of young deer (i.e., via stitched expansion folds and elastic materials), and eventually drop (i.e., via breakaway bands) after gradual expansion and deterioration of collar materials (Smith et al. 1998, Grovenberg et al. 2014). Researchers generally aim to obtain ≥12 weeks of survival and location data using radio-telemetry (Pusateri-Burroughs et al. 2006, Duquette et al. 2014, Grovenburg et al. 2014). However, premature loss or failure of expandable radio-collars has been reported in multiple studies (Vreeland et al. 2004, Pusateri-Burroughs et al. 2006, Rohm et al. 2007, Hiller et al. 2008, Grovenburg et al. 2014). Additional modifications to expandable collar designs for ungulates have been proposed to improve retention and facilitate a more gradual collar expansion, and some of these modifications have been deployed in captive studies and in the field (Diefenbach et al. 2003, Bowman et al. 2000, Cherry et al. 2014, Grovenburg et al. 2014, Kalb and Bowman 2014, Obermoller et al. 2018). For example, Diefenbach et al. (2003) tested an expandable radio-collar design (i.e., previously used on caribou [*Rangifer tarandus*]) on captive and free-ranging white-tailed deer in Pennsylvania, USA. During the first round of deployments, investigators determined these collars did not accommodate neck growth of fawns, but instead became restrictive within 60 days of life.

Diefenbach et al. (2003) deployed a modified collar design (i.e., improved stitching pattern to expand faster) on a second sample of fawns. Modified collars sufficiently expanded with neck growth of fawns and did not become restrictive, suggesting there would be minimal failure during the first 12 months of life (Diefenbach et al. 2003). These results highlighted the importance of using iterative processes (i.e., repetitive procedures intended to optimize the result) when testing collar designs. In addition, use of captive animals is preferable in the early stages of collar development. Utilizing captive fawns allows researchers to evaluate the efficacy of expandable collars over time, more closely observing collar fit and function and the overall health and well-being of fawns.

Integrating Global Positioning System (GPS) technology with expandable collar designs will allow more accurate and efficient investigation of fawn survival and reduce human error associated with radio-telemetry (Bowman et al. 2000, McCance and Baydack 2017). GPS collars are also more expensive compared to VHF collars; however, GPS provides more fine-scale and precise location data, improves efficiency, and reduces labor costs associated with VHF radio-telemetry (Bowman et al. 2000, Collins et al. 2014, McCance and Baydack 2017). Further research is warranted to study the fit and function of GPS-sized expandable collar designs in a fashion similar to previous collar studies, as the size and weight of batteries required to support this technology would be increased considerably. Increased battery weight applies greater pressure to the expandable materials of collars, potentially negatively impacting the performance and retention of collars (McCance and Baydack 2017). Aside from small experimental deployments (e.g., T. R. Obermoller, Minnesota Department of Natural Resources, unpublished data), GPS-sized collar designs have not been evaluated for white-tailed deer fawns. Newborn fawns are small in size, and increased collar weight may negatively impact behavior of fawns.

Therefore, testing GPS collars on neonatal white-tailed deer fawns in controlled settings is warranted to ensure animal welfare (e.g., monitor body condition, remove restrictive collars, etc.).

Preferential Acorn Consumption by Deer

Oaks (*Quercus* spp.) dominate many forests of the United States and have the greatest species diversity of all the woody genera (Abrams 1992, Cavender-Bares 2016, Hanberry and Nowacki 2016). Oaks have provided important ecosystem services throughout human history, providing consumable goods (e.g., food sources, materials for building, paper and ink, etc.), regulating environmental processes (e.g., carbon sequestration, absorption of atmospheric pollutants, persistence during fire, and reducing coastal erosion), and contributing to human culture (Cavender-Burns 2016, Hanberry and Nowacki 2016). Oaks also provide essential habitat (e.g., increased forest structure, cavities, and snags) for wildlife in hardwood forests (Cavender-Burns 2016, Hanberry and Nowacki 2016). Acorns produced by oaks are a highly valuable food source for many avian and mammal species in hardwood forests during the dormant season (McShea 2000, Haas and Heske 2005, McShea et al. 2007, Campbell and Wood 2013).

Acorn production by oaks directly correlates with movement, behavior, habitat use, and population sizes of deer in many portions of the southeastern United States (Miller et al. 1987, Wentworth et al. 1992, McShea et al. 2007). For example, McShea and Schwede (1993) determined that deer in Virginia, USA spent approximately 40% of their time feeding in forest stands composed primarily of oaks during the fall in years of above-average acorn production as opposed to <5% during years of below average acorn production. The abundance and diversity of acorn crops has also been shown to influence body weight, antler development, and reproduction in white-tailed deer in the Southern Appalachians (Anderson et al. 1991, Wentworth et al. 1992, Johnson et al. 1995). For example, weights of harvested fawns in deciduous hardwood forests of northwestern Tennessee, USA were directly correlated with the abundance of the prior year's acorn yield (Feldhamer et al. 1989, Campbell and Wood 2013). Because acorns are so important to white-tailed deer and other acorn-consuming species, localized declines in oak abundance observed in the parts of the southeastern United States are of concern (Martin et al. 1961, Pekins and Mautz 1987, Abrams 2003, McShea et al. 2007). The causes for these declines are not always apparent and the impacts on white-tailed deer populations in these areas could be significant (Haas and Heske 2005, McShea et al. 2007).

White-tailed deer numbers have increased considerably in much of the eastern United States over the last century, and higher deer densities can have notable effects on plant communities (Russell et al. 2001, Haas and Heske 2005, Crimmins et al. 2010, Taggart and Long 2015, Evans et al. 2016). High population densities of white-tailed deer can result in debilitating damage to tree regeneration and decreased survival of preferred plants because of herbivory by deer (Côte et al. 2004, Russell and Fowler 2004, Haas and Heske 2005, Dostaler et al. 2011, Taggart and Long 2015). Plant communities on the Southeastern barrier islands of the United States have been especially susceptible to deer herbivory because of poor soil quality and physical stress associated with the coastal environment (e.g., salt spray and shifting sediment; Ray et al. 2001, Taggart and Long 2015). On Cumberland Island, Georgia, USA, deer abundance declined >50% after the re-introduction of bobcats (*Lynx rufus*) in 1988–1989 (Diefenbach et al. 2013). Between 1990 and 1997, the number of live oak seedlings increased, suggesting that the re-introduction of bobcats caused a cascade effect related to deer predation, and subsequently increased oak regeneration (Diefenbach et al. 2009, Diefenbach et al. 2013). Alternatively, Taggart and Long (2015) found that after deer densities decreased on Bald Head Island, North

Carolina, USA, oak seedling survival was low, however deer did not negatively affect understory vegetation. Deer also consume acorns in hardwood ecosystems (McShea et al. 2007); however, estimates of the amounts and species of acorns consumed by animals are difficult to calculate and highly variable (Haas and Heske 2005). Therefore, it is challenging to develop a comprehensive understanding of the role selective acorn consumption plays in oak regeneration. Recent studies have reported decreased oak abundance in parts of the Southern Appalachians, which could be the result of changes in forest management practices, introduced diseases and pest species, or changes in climate (Fei et al. 2011). Deer have been shown to exacerbate existing declines of vulnerable (i.e., less tolerant to disturbance) oak species, such as white oak (*Q. alba*), through selective consumption of acorns in parts of the eastern United States (Whitney 1994, Abrams 2003). However, there is little literature addressing preferences of deer for other southeastern oak species, and even less about potential impacts of deer on oak regeneration through selective consumption of acorns.

OBJECTIVES

GPS Fawn Collars

I affixed expandable GPS collar mock-ups on captive white-tailed deer fawns and monitored collar fit and function during the first year of life. My objectives were to: 1) evaluate the efficacy of expandable GPS collar designs for white-tailed deer fawns, and 2) determine potential effects of collar mock-ups on the behavior of fawns.

Preferential Acorn Consumption by Deer

I conducted a series of cafeteria-style feeding preference trials with captive adult deer and evaluated acorn samples for nutritional composition. My objectives were to: 1) evaluate preferential consumption by white-tailed deer of 7 acorn species native to Georgia, and 2) characterize the nutritional composition of those acorns.

THESIS FORMAT

This thesis is presented in manuscript format. Chapter 1 includes an introduction to each study and a literature review of previous research focused on similar research topics. Chapter 2 reports on an evaluation of expandable GPS collars for white-tailed deer fawns. Chapter 3 reports on preferences of captive white-tailed deer for oak acorn species found in Georgia and nutritional analysis of those acorns. Chapter 4 summarizes conclusions and management implications of the results of these studies.

LITERATURE CITED

Abrams, M. D. 1992. Fire and the development of oak forests. Bioscience 42:346–353.

Abrams, M. D. 2003. Where has all the white oak gone? Bioscience 53:927–939.

Anderson, O. F., P. E. Hale, and A. S. Johnson. 1991. Acorn preferences of white-tailed deer: a preliminary report. Proceedings of the 14th Annual Southeast Deer Study Group, Baton Rouge, Louisiana, USA.

Bowman, J. L., C. O. Kochanny, S. Demarais, and B. D. Leopold. 2000. Evaluation of a GPS collar for white-tailed deer. Wildlife Society Bulletin 28:141–145.

Campbell, S. A. B., and T. C. Wood. 2013. Influences of precipitation, temperature, and acorn mast on white-tailed deer body weight in the Northern Piedmont of Virginia. Northeastern Naturalist 20:469–477.

Cavender-Bares, J. 2016. Diversity, distribution and ecosystem services of the North American oaks. International oaks 27:37–48.

Cherry, M. J., D. J. Morin, R. J. Warren, and L. M. Conner. 2014. A low-cost GPS solution for studying spatial ecology of white-tailed deer fawns. Proceedings of the 37th Southeast Deer Study Group Meeting. Southeastern Section of The Wildlife Society, 16–18 February 2014, Athens, Georgia, USA.

Chitwood, M. C., M. A. Lashley, J. C. Kilgo, C. E. Moorman, and C. S. DePerno. 2015. White-tailed deer population dynamics and adult female survival in the presence of a novel predator. Journal of Wildlife Management 79:211–219.

Collins, G. H., S. L. Petersen, C. A. Carr, and L. Pielstick. 2014. Testing VHF/GPS collar design and safety in the study of free-roaming horses. PLoS ONE 9:0103189.

Côte, S. D., T. P. Rooney, J. P. Tremblay, C. Dussault, and D. M. Waller. 2004. Ecological impacts of deer overabundance. Annual Review of Ecology, Evolution and Systematics 35:113–147.

Crimmons, S. M., J. W. Edwards, W. M. Ford, P. D. Keyser, and J. M. Crum. 2010. Browsing patterns of white-tailed deer following increased timber harvest and a decline in population density. International Journal of Forestry Research 2010:1–7.

Diefenbach, D. R., C. O. Kochanny, J. K. Vreeland, and B. D. Wallingford. 2003. Evaluation of an expandable, breakaway radiocollar for white-tailed deer fawns. Wildlife Society Bulletin 31:756–761.

Diefenbach, D. R., L. A. Hansen, C. Miller-Butterworth, J. H. Bohling, R. J. Warren, and M. J. Conroy. 2013. Re-introduction of bobcats to Cumberland Island, Georgia, USA: status and lessons learned after 25 years. Pages 235–240 *in* Global re-introduction perspectives 2013: Further case-studies from around the globe. 2013, International Union for Conservation of Nature, Gland, Switzerland.

Diefenbach, D. R., L.A. Hansen, R. J. Warren, M. J. Conroy, and M. G. Nelms. 2009. Restoration of bobcats to Cumberland Island, Georgia, USA: Lessons learned and evidence for the role of bobcats as keystone predators. Pages 423-425 *in* Iberian Lynx Ex situ Conservation: An interdisciplinary approach. 2009, Fundacion Biodiversidad, Madrid, Spain.

Dostaler, S., J. P. Ouellet, J. F. Therrien, and S. D. Cote. 2011. Are feeding preferences of white-tailed deer related to plant constituents? Journal of Wildlife Management 75:913–918.

Duquette, J. F., J. L. Belant, N. J. Svoboda, D. E. Beyer Jr., and P. E. Lederle. 2014. Effects of maternal nutrition, resource use and multi-predator risk on neonatal white-tailed deer survival. PLoS ONE 9:100841.

Evans, J. P., C. A. Oldfield, K. K. Cecala, J. K. Hiers, C. V. Ven, and M. M. Armistead. 2016. Pattern and drivers of white-tailed deer (*Odocoileus virginianus*) herbivory on tree saplings across a plateau landscape. Forests 7:1–12.

Fei, S., N. Kong, K. C. Steiner, W. K. Moser, and E. B. Steiner. 2011. Change in oak abundance in the eastern United States from 1980 to 2008. Forest Ecology and Management 262:1370–1377.

Feldhamer, G. A., T. P. Kilbane, and D. W. Sharp. 1989. Cumulative effect of winter on acorn yield and deer body weight. Journal of Wildlife Management 53:292–295.

Gingery, T. M., D. R., Diefenbach, B. D. Wallingford, and C. S. Rosenberry. 2018. Landscape-level patterns in fawn survival across North America. Journal of Wildlife Management 82:1003–1013.

Grovenburg, T. W., R. W. Claver, C. N. Jacques, T. J. Brinkman, C. C. Swanson, C. S. DePerno, K. L. Monteith, J. D. Sivers, V. C. Bleich, J. G. Kie, and J. A. Jenks. 2014. Influence of landscape characteristics on retention of expandable radiocollars on young ungulates. Wildlife Society Bulletin 38:89–95.

Gulsby, W. D., C. H. Killmaster, J. W. Bowers, J. D. Kelly, B. N. Sacks, M. J. Statham, and K. V. Miller. 2015. White-tailed deer fawn recruitment before and after experimental coyote removals in central Georgia. Wildlife Society Bulletin 39:248–255.

Haas, J. P., and E. J. Heske. 2005. Experimental study of the effects of mammalian acorn predators on red oak acorn survival and germination. Journal of Mammalogy 86:1015–1021.

Hanberry, B. B., and G. J. Nowacki. 2016. Oaks were the historical foundation genus of the east-central United States. Quaternary Science Reviews 145:94–103.

Hiller, T. L., H. Campa, III, and S. R. Winterstein. 2008. Survival and space use of fawn white-tailed deer in southern Michigan. American Midland Naturalist 159:403–412.

Jayne, K., and A. See. 2019. Behavioral research on captive animals: scientific and ethical concerns. Pages 517–548 *in* Animal Experimentation: Working Towards a Paradigm Change. Brill.

Johnson, A. S., P. E. Hale, W. M. Ford, J. M. Wentworth, J. R. French, O. F. Anderson, and G. B. Pullen. 1995. White-tailed deer foraging in relation to successional stage, overstory type and management of Southern Appalachian forests. American Midland Naturalist 133:18–35.

Kalb, D. M., and J. L. Bowman. 2014. Evaluating the effectiveness of expandable radiocollars for juvenile cervids. Wildlife Society Bulletin 38:857–961.

Kjellander, P., I. Svartholm, U. A. Bergvall, and A. Jarnemo. 2012. Habitat use, bed-site selection and mortality rate in neonate fallow deer *Dama dama*. Wildlife Biology 18:280–291.

Martin, A. C., H. C. Zim, and A. L. Nelson. 1961. American wildlife and plants: a guide to wildlife food habits. Dover Publications, New York, New York, USA.

McCance, E. C., and R. K. Baydack. 2017. Critical considerations for an urban deer collaring program. Environment and Ecology Research 5:195–203.

McShea, W. J., and G. Schwede. 1993. Variable acorn crops; responses of white-tailed deer and other mast consumers. Journal of Mammalogy 74:999–1006.

McShea, W. J. 2000. The influence of acorn crops on annual variation in rodent and bird populations. Ecological Society of America 81:228–238.

McShea, W. J., W. M. Healy, P. Devers, T. Fearer, F. H. Koch, D. Stauffer, and J. Waldon. 2007. Forestry matters: decline of oaks will impact wildlife in hardwood forests. Journal of Wildlife Management 71:1717–1728.

Miller, K. V., K. E. Kammermeyer, R. L. Marchington, and E. B. Moser. 1987. Population and habitat influences on antler rubbing by white-tailed deer. Journal of Wildlife Management 51:62–66.

Obermoller, T. R., G. D. DelGiudice, and W. J. Severud. 2018. Assessing expandable Global Positioning System collars for moose neonates: GPS Collars for moose neonates. Wildlife Society Bulletin 42:314–320.

Pekins, P. J., and W. W. Mautz. 1987. Acorn usage by deer: significance of oak management. Northern Journal of Applied Forestry 4:124–128.

Pusateri-Burroughs, J., H. Campa, III, S. R. Winterstein, B. A. Rudolph, and W. E. Moritz. 2006. Cause-specific mortality and survival of white-tailed deer fawns in southwestern lower Michigan. Journal of Wildlife Management 70:743–751.

Ray, D. K., E. G. Bolen, and W. D. Webster. 2001. Characteristics of a barrier island deer population in the southeastern United States. J. Elisha Mitchell Science Society 117:122–133.

Rodgers, A. R. 2001. Tracking animals with GPS: the first 10 years. Proceedings of An International Conference Held at The Macaulay Land Use Research Institute. 12–13 March 2001, Aberdeen, Scotland.

Rohm, J. H., C. K. Nielsen, and A. Woolf. 2007. Survival of white-tailed deer fawns in southern Illinois. Journal of Wildlife Management 71:851–860.

Russell, F. L., and N. L. Fowler. 2004. Effects of white-tailed deer on the population dynamics of acorns, seedlings and small saplings of *Quercus buckleyi*. Plant Ecology 173:59–72.

Russell, F. L. D. B. Zippin, and N. L. Fowler. 2001. Effects of white-tailed deer (*Odocoileus virginianus)* on plants, plant populations and communities: a review. American Midland Naturalist 146:1–26.

Scott, L. L., and F. D. Provenza. 2000. Lambs fed protein or energy imbalanced diets forage in locations and on foods that rectify imbalances. Applied Animal Behavior Science 68:293–305.

Smith, B. L., W. P. Burger, and F. J. Singer. 1998. An expandable radiocollar for elk calves. Wildlife Society Bulletin 26:113–117.

Swaisgood, R. R. 2007. Current status and future directions of applied behavioral research for animal welfare and conservation. Applied Animal Behaviour Science 102:139–162.

Taggart, J., and Z. Long. 2015. Effects of white-tailed deer (*Odocoileus virginianus*) on the maritime forest of Bald Head Island, North Carolina. American Midland Naturalist 173:283–293.

Vreeland, J. K., D. R. Diefenbach, and B. D. Wallingford. 2004. Survival rates, mortality causes, and habitats of Pennsylvania white-tailed deer fawns. Wildlife Society Bulletin 32:542–553.

Wentworth, J. M., A. S. Johnson, and P. E. Hale. 1992. Relationships of acorn abundance and deer herd characteristics in the Southern Appalachians. Southern Journal of Applied Forestry 16:5–8.

Whitney, G. G. 1994. From coastal wilderness to fruited plain. Cambridge University Press, Cambridge, United Kingdom.

CHAPTER 2

EVALUATION OF EXPANDABLE GPS COLLARS FOR WHITE-TAILED DEER FAWNS[1]

[1]Wesner, Z. G., A. S. Norton, T. R. Obermoller, D. A. Osborn, and G. J. D'Angelo.

To be submitted to *Wildlife Society Bulletin*.

ABSTRACT Integrating Global Positioning System (GPS) technology with expandable collars will allow researchers to more accurately and efficiently investigate survival of white-tailed deer (*Odocoileus virginianus*) fawns. We tested fit and function of 5 expandable GPS collar mock-up designs on white-tailed deer fawns and conducted behavioral observations of fawns at the Whitehall Deer Research Facility, Athens, GA, USA during 2018–2020. We fitted 46 fawns with 5 collar designs (20 Vectronic Vertex v1.0, 3 Telonics TGW v1.0, 3 Telonics Recon v1.0, 10 Vectronic Vertex v2.0, 10 Telonics TGW v2.0) and ear-tagged 15 control fawns without collars. Fawns retained Telonics v1.0 and v2.0 collars for a mean 101 (±46 [SD]) and 70 (±37) days, respectively. Fawns retained Vectronic v1.0 and v2.0 collars for a mean 246 (±156) and 306 (±99) days, respectively. Vectronic collared fawns were 10–11% more likely to be bedded than uncollared fawns. Bedded fawns with Vectronic (v1.0 and v2.0) and Telonics v2.0 collars were 20–41% more likely to exhibit a tucked head position and 22–42% less likely to have their head up than uncollared fawns. Collared fawns were 18–26% more likely to exhibit a head tilt than uncollared fawns. Vectronic (v1.0 and v2.0) and Telonics v2.0 collared fawns were 24–42% less vigilant and sleeping 25–48% more than uncollared fawns. We detected no other important differences in behavior (i.e., locomotion, suckling, grooming) between collared and uncollared fawns. All GPS collar designs we evaluated would benefit from additional modifications before deployment in the field, including improved stitching patterns and threads, smaller battery housings, improved weight distribution, and smaller band circumferences.

KEY WORDS behavior, expandable GPS collar, fawns, *Odocoileus virginianus*, white-tailed deer.

INTRODUCTION

Management of white-tailed deer (*Odocoileus virginianus*) requires a broad understanding of the parameters (e.g., abundance, vital rates, movements, habitat use) that define a population (Jacobson et al. 1997, Keyser et al. 2005). Fawn survival and recruitment are important vital rates influencing population growth (Rodgers et al. 1996, Bowman et al. 2000, Pusateri-Burroughs et al. 2006, Chitwood et al. 2015, Gulsby et al. 2015, Gingery et al. 2018). However, estimating survival of fawns to recruitment is challenging with traditional telemetry methods (i.e., radio-telemetry; Rodgers et al. 1996, Bowman et al. 2000, Pusateri-Burroughs et al. 2006). Additionally, delayed response times to mortality events decrease the quality of mortality assessments and samples (Severud et al. 2015). Movements and habitat use may directly impact fawn survival; however, fine-scale movements and resource selection of fawns is still poorly understood (Cherry et al. 2014). Traditional telemetry methods restrict the frequency of fix locations, reduce the accuracy and precision of locations, and may present biases by potentially affecting the behavior of fawns, their dams, or predators during data collection (Bowman et al. 2000, Rodgers 2001,).

Standard protocols for monitoring neonatal fawns include placing a very high frequency (VHF) radio-transmitter attached to an expandable band and monitoring fawns intensively using radio telemetry during the following months (Rodgers 2001, Pusateri-Burroughs et al. 2006). The expandable collar design is necessary because a deer's neck circumference increases rapidly with age, especially during the first year of life (Grovenburg et al. 2014). Expandable radio-collars are designed to gradually enlarge over time via expansion folds, ultimately dropping from the animal once collar materials have deteriorated (Smith et al. 1998, Grovenburg et al. 2014). Researchers often strive to obtain $\geq$12 weeks of survival and locational data on fawns (Pusateri-

Burroughs et al. 2006, Duquette et al. 2014, Grovenburg et al. 2014), but ideally, collars would be capable of collecting data for the entire first year of life. Premature loss or failure of expandable radiocollars for fawns has been reported in multiple studies (Vreeland et al. 2004, Pusateri-Burroughs et al. 2006, Rohm et al. 2007, Hiller et al. 2008, Grovenburg et al. 2014), reducing the sample size and power of inference. Additional modifications to expandable collar designs for ungulates have been proposed to improve retention and facilitate a more gradual collar expansion, and some of these modifications have been deployed in the field (Diefenbach et al. 2003, Kalb and Bowman 2014, Grovenburg et al. 2014, Obermoller et al. 2018).

Integrating expandable radio-collar designs with GPS technology would allow more accurate and efficient investigation of survival of white-tailed deer fawns and reduce human error associated with radio-telemetry (Bowman et al. 2000, McCance and Baydack 2017). The primary factor limiting use of GPS technology is the size and weight of the batteries required to support GPS transmitters (McCance and Baydack 2017). Additionally, GPS collars are much more expensive than VHF collars. However, GPS collars provide fine-scale locational data, improved efficiency, and reduced labor costs associated with radio-telemetry (Bowman et al. 2000; Collins et al. 2014; Severud et al. 2015; McCance and Baydack 2017). However, aside from small experimental deployments (e.g., T. R. Obermoller, Minnesota Department of Natural Resources, unpublished data), GPS-sized expandable radio-collar designs have not been fitted to white-tailed deer fawns. Until recently, expandable GPS collars have only been deployed on other neonatal ungulates in the field (moose [*Alces alces*], Severud et al. 2015, Obermoller et al. 2018; fallow deer [*Dama dama*], Kjellander et al. 2012) or in captivity (domestic horse [*Equus caballus*], Hampson et al. 2010).

In North America, white-tailed deer fawns are met with a host of threats to survival, especially predator species such as black bears (*Ursus americanus*), bobcats (*Lynx rufus*), cougars (*Puma concolor*), coyotes (*Canis latrans*), and wolves (*Canis lupus*, Pusateri-Burroughs et al. 2006, Duquette et al. 2014, Warbington et al. 2017, Soria-Diaz et al. 2018). White-tailed deer fawns are altricial and rely on cryptic tactics (i.e., camouflage and optimal body orientation) and alertness (i.e., vigilance) to avoid potential predators (White et al. 1972). The typical orientation of a bedded fawn is low to the ground, with the head resting in a curled (i.e., tucked) position and their head upright against their side (White et al. 1972). By the time they are a few days old, neonatal fawns may also attempt to escape disturbances by fleeing short distances (i.e., 10–50 meters) and then dropping down to hide (White et al. 1972). Therefore, development and deployment of GPS-sized collars on fawns should consider potential impacts on fawn behavior to avoid biases in their susceptibility to predation because they may orient differently, be less vigilant, or encumbered in escape.

Utilizing captive fawns allows for evaluation of the efficacy of expandable GPS collars over time and observation of collar fit and function, the overall health and well-being of fawns, and the impact of collars on fawn behavior. In addition, collars that become overly restrictive on captive fawns may be safely removed. Most prior studies deploying GPS collars on neonatal ungulates involved animals considerably larger than white-tailed deer (Hampson et al. 2010, Kjellander et al. 2012, Severud et al. 2015, Obermoller et al. 2018) which may be better able to support the mass of a GPS collar. Therefore, testing GPS collars on white-tailed deer fawns in a controlled setting is warranted to ensure animal welfare for the duration of collar evaluations.

We affixed expandable GPS collar mock-ups on captive white-tailed deer fawns and monitored them during the first year of life. Our primary study objectives were to: 1) evaluate the efficacy of expandable GPS collar designs for white-tailed deer fawns, and 2) determine potential effects of collar mock-ups on the orientation and behavior of fawns.

METHODS

Study Site

We conducted our study at the Whitehall Deer Research Facility on the University of Georgia campus in Athens, Georgia, USA (83°21'13.0"W, 33°53'18.7"N). The facility is approximately 2.4 ha surrounded by 3-m-high woven-wire fencing. We housed captive deer in 0.4–0.8-ha outdoor paddocks (12–14 adult deer each). We provided deer with pelleted feed (Purina AntlerMax Deer Breeder Textured 17-6, Gainesville, GA, USA), perennial peanut hay, and water *ad libitum*.

Animal Capture and Handling

We searched outdoor paddocks for newborn fawns twice daily during May–July 2018 and 2019. We captured, handled, and released each fawn ≤24 hr after birth. We collected weights and morphometric measurements of fawns (i.e., total body length, chest girth, hindfoot length, and neck circumference at upper, middle, and lower neck), affixed individually identifying ear tags in one or both ears (Allflex USA Inc., DFW Airport, TX, USA), and fitted fawns with expandable GPS collar mock-ups. We also handled and ear-tagged a subset of fawns not fitted with collars to serve as controls during behavioral assessments. After handling, we immediately returned fawns to outdoor paddocks and reunited them with their dam. All methods were approved by the University of Georgia Institutional Animal Care and Use Committee under Animal Use Proposal A2018 03-019-Y2-A0.

Collar Fit and Function

We assessed collar fit and function 3–5 times per week on each fawn through 12 months of age. We remotely observed fawns in outdoor paddocks, evaluated collar fit and body condition, and examined each fawn's neck for signs of hair loss or lesions (Table 2.1). We recorded when collars failed (i.e., shed or required removal to ensure animal welfare). We captured fawns at approximately 6, 9, and 12 months of age and manually restrained them to inspect the integrity of collars, evaluate the condition of fawns, and collect neck circumference measurements.

Vectronic Vertex

We tested collar designs from 2 manufacturers: Vectronics and Telonics. The Vectronic Vertex v1.0 (Vectronic Aerospace GmbH, Berlin, Germany; Fig. 2.1) collars weighed approximately 138 g, with the mock-up of the battery, VHF transmitter, and GPS transmitter located within a single large housing (6.2 cm × 3.9 cm × 4.4 cm) at the front of the collar. The housing was attached to the collar using high-performance glue and 2 plastic cable ties. The antenna was coated with a thin protective layer of plastic and measured 20.5 cm. The neck band was 4-cm wide, composed of nylon and rubber (i.e., elasthodiene) materials with an initial circumference of 22.3 cm. The neck band included 6 expansion folds (3 sections of 2 folds each), which were 2-cm long. The section of folds furthest from the housing had a single straight stitch (i.e., parallel to long-axis) running through the middle of its folds, the middle section had 2 parallel straight stitches (2.4-cm apart) running through its folds, and the section closest to the housing had 2 parallel straight stitches (3.1-cm apart) running through its folds. Fully expanded, the circumference of the neck band was approximately 34 cm, not including stretch of the elastic band material. The measurements of Vectronic Vertex v2.0 (Vectronic Aerospace GmbH, Berlin, Germany; Fig. 2.2) were identical to the Vertex v1.0, except the battery housing of the updated design was slightly larger in size (6.5 cm × 4.2 cm × 4.4 cm) and 15 g heavier (153 g) than the Vertex v1.0.

Telonics TGW and Recon

Telonics TGW v1.0 (Telonics, Inc., Mesa, AZ, USA; Fig. 2.1) and Telonics Recon v1.0 (Telonics, Inc., Mesa, AZ, USA, Fig. 2.1) collars weighed about 140 g and 150 g, respectively. The primary differences between the TGW v1.0 and the Recon v1.0 designs were the battery housing material and the distribution of mock-up electronics. The Telonics TGW v1.0 battery, VHF transmitter and GPS transmitter were located in 3 housings: a polymeric housing contained the battery (5.5 cm × 2.9 cm × 3.3 cm) and 2 plastic housings contained the VHF (dimensions = 1.8 cm × 0.5 cm × 1.8 cm) and GPS (2.8 cm × 0.9 cm × 2.8 cm) transmitters. The Telonics Recon v1.0 battery, VHF and GPS transmitters were distributed between only 2 housings: an aluminum housing contained both the battery and the VHF transmitter (4.3 cm × 2.6 cm × 3.5 cm) and a plastic housing contained the GPS transmitter (2.8 cm × 0.9 cm × 2.8 cm). The battery housings of both the TGW v1.0 and the Recon v1.0 designs were attached to the collar using 4 screws and glue. The antenna measured 20.9 cm. The expandable collar bands (7.9 cm × 7.9 cm) were composed of cotton and rubber (i.e., elasthodiene) sewn to a strip of static polymer (15.0 cm × 3.7 cm). Therefore, the initial band circumference (i.e., pre-expansion) of each model was 22.9 cm and included 6 expansion folds (i.e., 3 sections of 2 folds each), which were 2-cm long. The section of folds closest to the housing had a single straight stitch running through the middle of its folds, the middle section had 2 parallel straight stitches (1-cm apart) running through its folds, and the section furthest from the housing had 4 parallel straight stitches (0.5-cm apart) running through its folds. Fully expanded, the circumference was 34.9 cm, not including stretch of the elastic band material. The measurements for the Telonics TGW 2.0 (Telonics, Inc., Mesa, AZ, USA; Fig. 2.2) were identical to the TGW v1.0, except it utilized 3 protruding expansion folds designed to allow more initial stretching. The TGW v2.0 used nylon thread stitched perpendicular to the long axis, and was 4 g lighter (136 g) than the TGW v1.0.

Study Animals

We captured and monitored a total of 61 (31 during 2018–2019 and 30 during 2019–2020) fawns during 2018–2020. We fitted 20 fawns with Vectronic Vertex v1.0 collars, 3 fawns with Telonics TGW v1.0 collars, 3 fawns with Telonics Recon v1.0 collars, and ear-tagged 5 control fawns without collars during 2018. We fitted 10 fawns with Vectronic Vertex v2.0 collars, 10 fawns with Telonics TGW v2.0 collars, and ear-tagged 10 control fawns without collars during 2019. We captured 35 additional neonates at the facility to collect their weights and neck measurements.

Fawn Orientation and Behavior

We conducted focal observation sessions of collared and uncollared fawns 3 times per week during the first 4 weeks of life. We conducted observations from 4.5-m stationary observation platforms between 0600 hr to 1000 hr. We positioned an observation platform in each of 2 connected paddocks holding fawns. We determined the placement of the platforms based on optimal viewing opportunities and proximity to the entrance of the paddock. We alternated between the 2 platforms to determine position at the start of sampling periods (i.e., from day-to-day), and visually scanned paddocks for fawns, starting scans from east to west or west to east (alternating direction every 2 sampling periods). Before conducting the first behavioral observation of a sampling period, the observer sat quietly for 15 min to minimize impacts of human activity on the behavior of deer in the paddocks. We recorded a single score of body orientation for each position (i.e., body position, head position, and head tilt, Fig. 2.3) and a single score of "1" (behavior present) or "0" (behavior absent) for each possible behavior (Table 2.2) for the focal fawn. If a fawn was not in view from the starting platform, the observer would move to the second platform, allow the deer to settle again for 15 min, then proceed with observations. If a fawn was not in view during a sampling period, we did not collect behavioral data for that individual.

Data Analysis

We analyzed data using program R 4.0.3 (R Core Team 2020). We calculated mean (SE) neck circumference measurements from fawns at approximately 0, 6, 9, and 12 months of age. We calculated mean (SE) dates at which collars failed, dropped, or required removal. We combined all fawns with Telonics v1.0 collars (TGW and Recon) into one group (Telonics v1.0) for body orientation and behavioral analyses because of low sample sizes due to limited collar availability, and since collars were similar. We analyzed fawn body position (i.e., 0 = bedded or 1 = standing) using generalized linear mixed models (GLMM's) with collar model (i.e., Vectronic v1.0, Telonics v1.0, Vectronic v2.0, Telonics v2.0, and uncollared [i.e., reference level]) as the independent variable, and time (i.e., week) and sex (i.e., male or female) as covariates. We analyzed head position (i.e., 0 = tucked, 1 = down, or 2 = up) and head tilt (i.e., 0 = no tilt, 1 = slight tilt, or 2 = severe tilt) of bedded fawns and head position (i.e., 0 = tucked, 1 = down, or 2 = up) of standing fawns each using multinomial logistic regressions with collar model as the independent variable, and time and sex as covariates. We set the reference levels in each set of models for head position (bedded), head tilt (bedded), and head position (standing) at 0. We determined reference levels based on which positions we expected to observe most frequently for uncollared fawns during behavioral assessments. We analyzed the presence (i.e., 1) and absence (i.e., 0) of each fawn behavior (e.g., vigilant, sleeping, locomotion, suckling) using a series of GLMM's with collar model as the independent variable, fawn identification as a random factor, and time and sex as covariates. We used Akaike's Information Criterion (AIC) to determine the best-fit models for each aspect of body orientation and for each behavior.

RESULTS

Collar Fit and Function

Fawns weighed a mean 2.9 (±0.5 [SD]) kg at birth, and the collars we tested were a mean 4.9% of the mean newborn weight. Initial collar band circumferences (i.e., pre-expansion) were 3.6–6.4 cm (3.6–5.8 cm for Vectronic, 4.2–6.4 cm for Telonics) larger than the average fawn's neck at birth, depending on the position of the collar along the neck (Table 2.3). Fawns shed 2 Telonics v2.0 collars at 5 and 17 days, prior to any collar expansion. We observed full expansion of the collar folds of all 6 Telonics v1.0 collars by mean 76 (±28 [±SD]) days, while 8 of 10 Telonics v2.0 collars were fully expanded by mean 47 (±25) days. Of the remaining collars, all fawns stepped through the Telonics collars (v1.0 and v2.0) with one or both forelimbs, and collars ended up around the chest or waist. Coat-thinning followed by large bald patches around the area of the collar was prevalent in fawns with Telonics collars (post-expansion), and in one instance, a laceration formed and became infected under a deer's forelimb where the collar had rubbed. One Telonics v1.0 collar shed at 80 days and 6 Telonics v2.0 collars shed by mean 62 (±17) days due to poor fit. We removed all remaining Telonics (v1.0 and v2.0) collars at approximately 6 months of age. Fawns retained Telonics v1.0 and v2.0 collars for a mean 101 (±46) and 70 (±37) days, respectively, before collars failed (i.e., shed or required removal).

No Vectronic (v1.0 and v2.0) collars shed prior to collar expansion. As Vectronic collar folds expanded, minor hair loss (i.e., coat thinning) was often observed initially; however, the necks of fawns grew into expanded collars at a satisfactory rate, fit was acceptable, and hair grew back. One Vectronic v1.0 collar shed at 261 days and 1 Vectronic v2.0 collar shed at 109 days due to unknown causes. Two Vectronic v1.0 collars and 2 Vectronic v2.0 collars shed from fawns by snagging on the perimeter fencing at the captive facility while moving deer to collect neck measurements (i.e., 3 shed at approximately 6 months and 1 at approximately 9 months). Fawns retained Vectronic v1.0 and v2.0 collars for mean 246 (±156) and 306 (±99) days, respectively, before collars failed. Fawns retained 10 Vectronic v1.0 collars and 7 Vectronic v2.0 collars for >365 days. Fully expanded (i.e., not including stretch of elastic) Vectronic collar band circumferences were 3.9-cm smaller to 3.7-cm larger than the average fawn's neck at 12 months of age, however, with gradual wear and exposure to the elements, elastic materials sufficiently stretched and accommodated neck growth of fawns.

Fawn Orientation and Behavior

The best-fit model for body position by collar group included sex as a covariate and deer identification as a random factor (AIC_c = 352.66, Table 2.4). Vectronic collared fawns were 10–11% more likely to be bedded than uncollared fawns (Table 2.5, Fig. 2.4). Body position did not differ between Telonics collared fawns and uncollared fawns (Table 2.5, Fig. 2.4). Male fawns were more frequently observed standing than female fawns (Table 2.5). The best-fit models for analyses of head position (i.e., bedded and standing) and head tilt (bedded) included collar group as the independent variable with no additional covariates (AIC_c = 627.12, 111.72, and 570.19, respectively, Table 2.6). Bedded fawns with Vectronic (v1.0 and v2.0) and Telonics v2.0 collars were 32–41% and 20%, respectively, more likely to exhibit a tucked head position than uncollared fawns (Table 2.7, Fig. 2.5). Additionally, bedded fawns with Vectronic (v1.0 and v2.0) and Telonics v2.0 collars were 36–42% and 22%, respectively, less likely to have their head up than uncollared fawns (Table 2.7, Fig. 2.5). Head position of bedded fawns did not differ between fawns with Telonics v1.0 collars and uncollared fawns (Table 2.7, Fig. 2.5). All collared fawns were 18–26% more likely to exhibit a slight head tilt when bedded than uncollared fawns (Table 2.7, Fig. 2.5). Standing Telonics v1.0 collared fawns were approximately 50% more likely to exhibit a tucked head position than uncollared fawns (Table 2.7, Fig. 2.5). We observed no other significant differences in head position when fawns were standing between collared and uncollared fawns (Table 2.7, Fig. 2.5).

The best-fit models for each fawn behavior by collar group included deer identification as a random factor with no additional covariates (AIC_c = 545.63 and 565.71, respectively, Table 2.8). Vectronic (v1.0 and v2.0) and Telonics v2.0 collared fawns were 35–42% and 24%, respectively, less vigilant than uncollared fawns, and sleeping 30–48% and 25%, respectively, more than uncollared fawns (Table 2.9, Fig. 2.6). We observed no significant differences in vigilance or sleeping between Telonics v1.0 collared fawns and uncollared fawns (Table 2.9, Fig. 2.6).

Other notable effects of collars on fawn behavior included exaggerated high-stepping with forelimbs during locomotion and numerous instances of forelimbs getting caught in ill-fitting collars (i.e., pre-expansion, Table 2.10). Of the 16 Telonics (v1.0 and v2.0) collared fawns, 31% exhibited high-stepping for a total of 18 occurrences, while 63% of the 30 Vectronic (v1.0 and v2.0) collared fawns exhibited high-stepping for a total of 31 occurrences (Table 2.9). No uncollared fawns exhibited high-stepping behavior. Of the 16 Telonics (v1.0 and v2.0) collared fawns, 38% experienced a forelimb caught in a collar band (9 occurrences), and 13% of

Vectronic (v1.0 and v2.0) collared fawns were observed with a forelimb caught in a collar band (4 occurrences; Table 2.10). We detected no other important differences in behavior (i.e., locomotion, suckling, groomed, grooming) between collared and uncollared fawns (Table 2.9).

DISCUSSION

Based on our observations, we would not recommend the use of the expandable GPS collar designs evaluated in this study for use in the field. However, researchers may have access to viable GPS fawn collar options with incorporation of design modifications and further testing in controlled settings. Premature expansion and breakage of Telonics collars was a problem which resulted in hair loss caused by freely moving collars, collar displacement from the neck to the mid-section, and a severe laceration on one fawn. We did not observe similar issues with fit and function in Vectronic collars. With a few exceptions, Vectronic collars were sufficiently retained by fawns. However, Vectronic (v1.0 and v2.0) and Telonics v2.0 collared fawns were less alert and less active and exhibited tucked and slightly tilted head positions more often compared to uncollared fawns. Thus, fawns with collars may be less likely to detect potential dangers (e.g., predators).

Exaggerated high-stepping during locomotion by GPS-collared fawns appeared to be attributable to heavy, loose-fitting collars swinging freely on the necks of fawns. This exaggerated gait also likely would make wild fawns fitted with GPS collars more susceptible to predation. Similarly, fawns with restrained forelimb(s) due to poor collar fit may be unable to evade predation. All of the abnormal behaviors observed by GPS-collared fawns likely would provide a significant bias in estimating predation rates.

To refine development of future GPS collar designs for white-tailed deer fawns, we recommend reducing the overall size and weight of collars, understanding there are limitations associated with battery size and collar functionality. In addition, improved weight distribution around the collar (e.g., similar to layout of Telonics designs, Figures 2.3–2.5) may help reduce potential impacts on orientation (e.g., body position, head position, head tilt) and behavior (e.g., vigilance, sleeping, high-stepping) of fawns. We further recommend smaller initial collar band circumferences (as reported herein and by Diefenbach et al. 2003) to minimize hair loss caused by rubbing, to decrease risks of collar displacement and failure, and to reduce the potential for fawns catching forelimbs in loose-fitting collars. Smaller initial collar band circumferences might also minimize unusual behaviors like the exaggerated high-stepping we observed in collared fawns. Size requirements for collars for white-tailed deer fawns will likely vary by region (Strickland and Demarais 2000, Wolverton et al. 2009). Although, mean neck measurements of fawns reported by Diefenbach et al. (2003) in Pennsylvania, USA were comparable to lower neck measurements of fawns in our study. We recommend use of improved stitching patterns and more durable thread and elastic materials on collar bands (e.g., similar to Vectronic designs, Fig. 2.1–2.2) to promote more gradual expansion, thereby minimizing hair loss, collar displacement, and forelimb restraint, and increasing collar retention.

We encourage improved communication between researchers and telemetry technology suppliers, especially during development of collar designs. For example, companies should strive to be receptive to observations of researchers to help meet their concerns of animal welfare and potential study bias. Researchers should understand the limitations of current collar technology. We also encourage researchers to communicate more frequently with one another to discuss expandable collar designs, preventing wasteful spending and saving of time and effort. We propose implementation of iterative processes in collar design, including a preliminary Phase I that utilizes captive animals to test initial collar designs, a subsequent Phase II that incorporates modifications to initial collar designs and further testing in captivity, and Phase III as a limited pilot deployment in a field study. Prior to Phase III, collars should meet all appropriate, pre-determined standards.

Finally, we recommend testing of traditional VHF collars similar to the procedure presented here. Researchers have used VHF collar technology extensively in ungulate research since the late 1980s (Rodgers 2001). If previous collar designs had functional and behavioral impacts on fawns similar to what was observed in this study, validity of prior survival estimates may be suspect. If collared fawns are more susceptible to mortality (e.g., due to decreased vigilance and ability to escape predation) compared to uncollared fawns, studies may have underestimated survival of fawns. Conversely, if collared fawns are less susceptible to mortality (e.g., due to more time spent bedded and decreased activity), studies may have overestimated survival. Limited availability of fawns prevented testing of VHF collars in this study.

MANAGEMENT IMPLICATIONS

VHF technology limits the ability to efficiently estimate fawn survival, recruitment, movements, and habitat use. Integrating GPS technology with expandable collar designs would provide more accurate information regarding survival and behavior of fawns. Considering the issues with collar size, weight, band integrity, animal welfare, and behavioral impacts, further testing of GPS collar designs for fawns in controlled settings is warranted before extensive deployment in field studies.

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LITERATURE CITED

Bowman, J. L., C. O. Kochanny, S. Demarais, and B. D. Leopold. 2000. Evaluation of a GPS collar for white-tailed deer. Wildlife Society Bulletin 28:141–145.

Cherry, M. J., D. J. Morin, R. J. Warren, and L. M. Conner. 2014. A low-cost GPS solution for studying spatial ecology of white-tailed deer fawns. Proceedings of the 37th Southeast Deer Study Group Meeting. Southeastern Section of The Wildlife Society, 16–18 February 2014, Athens, Georgia, USA.

Chitwood, M. C., M. A. Lashley, J. C. Kilgo, C. E. Moorman, and C. S. DePerno. 2015. White-tailed deer population dynamics and adult female survival in the presence of a novel predator. Journal of Wildlife Management 79:211–219.

Collins, G. H., S. L. Petersen, C. A. Carr, and L. Pielstick. 2014. Testing VHF/GPS collar design and safety in the study of free-roaming horses. PLoS ONE 9:0103189.

Duquette, J. F., J. L. Belant, N. J. Svoboda, D. E. Beyer Jr., and P. E. Lederle. 2014. Effects of maternal nutrition, resource use and multi-predator risk on neonatal white-tailed deer survival. PLoS ONE 9:100841.

Diefenbach, D. R., C. O. Kochanny, J. K. Vreeland, and B. D. Wallingford. 2003. Evaluation of an expandable, breakaway radiocollar for white-tailed deer fawns. Wildlife Society Bulletin 31:756–761.

Gingery, T. M., D. R., Diefenbach, B. D. Wallingford, and C. S. Rosenberry. 2018. Landscape-level patterns in fawn survival across North America. Journal of Wildlife Management 82:1003–1013.

Grovenburg, T. W., R. W. Claver, C. N. Jacques, T. J. Brinkman, C. C. Swanson, C. S. DePerno, K. L. Monteith, J. D. Sivers, V. C. Bleich, J. G. Kie, and J. A. Jenks. 2014. Influence of landscape characteristics on retention of expandable radiocollars on young ungulates. Wildlife Society Bulletin 38:89–95.

Gulsby, W. D., C. H. Killmaster, J. W. Bowers, J. D. Kelly, B. N. Sacks, M. J. Statham, and K. V. Miller. 2015. White-tailed deer fawn recruitment before and after experimental coyote removals in central Georgia. Wildlife Society Bulletin 39:248–255.

Hampson, B., J. Morton, P. Mills, M. Trotter, D. Lamb, and C. Pollitt. 2010. Monitoring distances travelled by horses using GPS tracking collars. Australian Veterinary Journal 88:176–181.

Hiller, T. L., H. Campa, III, and S. R. Winterstein. 2008. Survival and space use of fawn white-tailed deer in southern Michigan. American Midland Naturalist 159:403–412.

Jacobson, H. A., J. C. Kroll, R. W. Browning, B. H. Koerth, and M. H. Conway. 1997. Infrared-triggered cameras for censusing white-tailed deer. Wildlife Society Bulletin 25:547–556.

Kalb, D. M., and J. L. Bowman. 2014. Evaluating the effectiveness of expandable radiocollars for juvenile cervids. Wildlife Society Bulletin 38:857–961.

Keyser, P. D., D. C. Guynn Jr., and H. S. Hill Jr. 2005. Population density-physical condition relationships in white-tailed deer. Journal of Wildlife Management 69:356–365.

Kjellander, P., I. Svartholm, U. A. Bergvall, and A. Jarnemo. 2012. Habitat use, bed-site selection and mortality rate in neonate fallow deer *Dama dama*. Wildlife Biology 18:280–291.

McCance, E. C., and R. K. Baydack. 2017. Critical considerations for an urban deer collaring program. Environment and Ecology Research 5:195–203.

Obermoller, T. R., G. D. DelGiudice, and W. J. Severud. 2018. Assessing expandable Global Positioning System collars for moose neonates: GPS Collars for moose neonates. Wildlife Society Bulletin 42:314–320.

Pusateri-Burroughs, J., H. Campa, III, S. R. Winterstein, B. A. Rudolph, and W. E. Moritz. 2006. Cause-specific mortality and survival of white-tailed deer fawns in southwestern lower Michigan. Journal of Wildlife Management 70:743–751.

Rodgers, A. R. 2001. Tracking animals with GPS: the first 10 years. Proceedings of An International Conference Held at The Macaulay Land Use Research Institute. 12–13 March 2001, Aberdeen, Scotland.

Rodgers, A. R., R. S. Rempel, and K. F. Abraham. 1996. A GPS-based telemetry system. Wildlife Society Bulletin 24:559–566.

Rohm, J. H., C. K. Nielsen, and A. Woolf. 2007. Survival of white-tailed deer fawns in southern Illinois. Journal of Wildlife Management 71:851–860.

Severud, W. J., G. D. DelGiudice, T. R. Obermoller, T. A. Enright, R. G. Wright, and J. D. Forester. 2015. Using GPS collars to determine parturition and cause-specific mortality of moose calves. Wildlife Society Bulletin 39:616–625.

Soria-Diaz, L., M. S. Fowler, O. Monroy-Vilchis, and D. Oro. 2018. Functional responses of cougars (*Puma concolor*) in a multiple prey-species system. Integrative Zoology 13:84–93.

Strickland, B. K., and S. Demarais. 2000. Age and regional differences in antlers and mass of white-tailed deer. Journal of Wildlife Management 64:903–911.

Vreeland, J. K., D. R. Diefenbach, and B. D. Wallingford. 2004. Survival rates, mortality causes, and habitats of Pennsylvania white-tailed deer fawns. Wildlife Society Bulletin 32:542–553.

Warbington, C. H., T. R. Van Deelen, A. S. Norton, J. L. Sténglein, D. J. Storm, and K. J. Martin. 2017. Cause-specific neonatal mortality of white-tailed deer in Wisconsin, USA. Journal of Wildlife Management 81:824–833.

White, M., F. F. Knowlton, and W. C. Glazener. 1972. Effects of dam-newborn fawn behavior on capture and mortality. Journal of Wildlife Management 36:897–906.

Wolverton, S., M. A. Huston, J. H. Kennedy, K. Cagle, and J. D. Cornelius. 2009. Conformation to Bergmann's rule in white-tailed deer can be explained by food availability. American Midland Naturalist 162:403–417.

Table 2.1. Assessments of collar fit, body condition, neck hair loss, and neck lesions used to monitor welfare of white-tailed deer fawns during testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020.

Collar Fit	Body Condition	Neck Hair Loss	Neck Lesions
Very loose	Emaciated	No hair loss	No lesions
Little loose	Thin	Coat thinning	Single ≤1cm
Good fit	Prime	Single bald patch ≤1 cm	Multiple ≤1cm
Little tight	Heavy	Bald patches ≤1cm	Single >1cm
Very tight	Obese	Bald patch(es) >1cm	Multiple >1cm

Table 2.2. Ethogram used for categorizing behaviors of white-tailed deer fawns for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020.

Behavior	Definition
Locomotion	Focal fawn was moving forward (e.g., walking, etc.)
Suckling	Focal fawn was actively suckling at adult doe
Grooming	Focal fawn was grooming itself
Groomed	Focal fawn was being groomed by another deer
Vigilant	Focal fawn had eyes open and appeared to be alert
Sleeping	Focal fawn had eyes closed and appeared to be asleep

Table 2.3. Mean (±SD) neck measurements (i.e., upper neck, middle neck, lower neck) collected from white-tailed deer fawns (including fawns born at the facility, but not used further in this study) at birth and at approximately 6, 9, and 12 months of age, including the total number of fawns measured at each time interval for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020.

		Neck circumference (cm)		
Age (months)	No. fawns	Upper	Middle	Lower
0	96	16.5 ± 1.5	16.7 ± 1.6	18.7 ± 1.8
6	50	25.5 ± 2.4	26.1 ± 2.7	30.9 ± 3.6
9	39	29.4 ± 3.1	30.6 ± 3.1	36.8 ± 4.3
12	18	31.4 ± 2.7	31.0 ± 2.6	38.6 ± 4.2

Table 2.4. Model selection results from a generalized linear mixed model analysis of body position (i.e., 0 = bedded or 1 = standing) of white-tailed deer fawns wearing GPS collars and uncollared fawns during the first 4 weeks of life for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020. We used Akaike's Information Criterion (AIC) to determine the best-fit model. Shown are number of parameters (*K*), Akaike's Information Criteria for small sample sizes (AIC_c), differences among AIC_c (ΔAIC), AIC_c weights (ω_i), and cumulative AIC_c weights (CumWt).

Model	*K*	AIC_c	ΔAIC	ω_i	CumWt
Collar + sex	7	352.66	0.00	0.67	0.67
Collar + week + sex	8	354.39	1.73	0.28	0.95
Collar	6	358.42	5.76	0.04	0.99
Collar × week + sex	12	360.92	8.26	0.01	1.00
Collar × week	11	366.67	14.01	0.00	1.00

Table 2.5. Differences in body position (i.e., 0 = bedded or 1 = standing) between sexes and between white-tailed deer fawns wearing GPS collars (i.e., Telonics v1.0 [T1]; Telonics v2.0 [T2]; Vectronic v1.0 [V1]; Vectronic v2.0 [V2]) and uncollared (UC [i.e., reference level]) fawns during the first 4 weeks of life, based on mean estimates from the best-fit generalized linear mixed model (i.e., Body Position ~ Collar + Sex) for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020. Shown are regression coefficients (β), standard error (SE), Z-scores, and P-values.

	Response level = 1 (standing)			
Collar	β	SE	Z	P
UC	-1.8	0.30	-5.88	< 0.001
T1	0.0	0.55	-0.07	0.941
T2	-0.7	0.36	-1.82	0.069
V1	-1.3	0.56	-2.29	0.022 *
V2	-1.4	0.40	-3.44	< 0.001 *
Sex (M)	0.8	0.31	2.69	0.007 *

*Significant differences detected by the best-fit model ($P \leq 0.05$).

Table 2.6. Model selection results from a multinomial linear regression analyses of head position and head tilt of white-tailed deer fawns wearing GPS collars and uncollared fawns during the first 4 weeks of life for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020. We used Akaike's Information Criterion (AIC) to determine the best-fit model for each candidate set. Shown are number of parameters (*K*), Akaike's Information Criteria for small sample sizes (AIC_c), differences among AIC_c (ΔAIC), AIC_c weights (ω_i), and cumulative AIC_c weights (CumWt).

Position	Model	*K*	AIC_c	ΔAIC	ω_i	CumWt.
Head	Collar	10	627.12	0.00	0.75	-303.26
(bedded)	Collar + sex	12	629.60	2.48	0.22	-302.38
	Collar + week + sex	14	633.62	6.50	0.03	-302.24
	Collar × week	20	638.68	11.57	0.00	-298.18
	Collar × week + sex	22	641.24	14.12	0.00	-297.21
Head tilt	Collar	10	570.19	0.00	0.87	0.87
(bedded)	Collar + sex	12	574.32	4.13	0.11	0.98
	Collar + week + sex	14	577.55	7.36	0.02	1.00
	Collar × week	20	589.23	19.03	0.00	1.00
	Collar × week + sex	22	593.60	23.41	0.00	1.00
Head	Collar	10	111.72	0.00	0.95	0.95
(standing)	Collar + sex	12	117.56	5.83	0.05	1.00
	Collar + week + sex	14	123.98	12.26	0.00	1.00
	Collar × week	20	133.20	21.48	0.00	1.00
	Collar × week + sex	22	141.63	29.90	0.00	1.00

Table 2.7. Differences in head position and head tilt between white-tailed deer fawns wearing GPS collars (i.e., Telonics v1.0 [T1]; Telonics v2.0 [T2]; Vectronic v1.0 [V1]; Vectronic v2.0 [V2]) and uncollared (UC) fawns during the first 4 weeks of life, based on mean estimates from the best-fit multinomial linear regression (i.e., Head Position ~ Collar) for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020. Shown are regression coefficients (β), standard error (SE), Z-scores, and P-values.

		Response level = 1[a]				Response level = 2			
Position	Collar	β	SE	Z	P	β	SE	Z	P
Head	UC	-2.1	0.48	-4.32	< 0.001	0.5	0.20	2.44	0.015
(bed)	T1	0.7	0.92	0.72	0.469	-0.4	0.53	-0.72	0.474
	T2	-0.1	0.64	-0.10	0.918	-0.9	0.30	-3.01	0.003 *
	V1	0.0	0.67	0.04	0.969	-1.6	0.38	-4.12	< 0.001 *
	V2	-0.6	0.64	-0.96	0.338	-2.0	0.32	-6.17	< 0.001 *
Head tilt	UC	-3.6	0.59	-6.07	< 0.001	-12.9	62.78	-0.21	0.837
(bed)	T1	2.5	0.83	3.07	0.002 *	11.9	62.79	0.19	0.849
	T2	2.5	0.64	3.94	< 0.001 *	11.5	62.78	0.18	0.855
	V1	3.0	0.66	4.46	< 0.001 *	12.0	62.79	0.19	0.849
	V2	2.7	0.63	4.30	< 0.001 *	11.6	62.78	0.18	0.854
Head	UC	0.9	0.84	1.10	0.27	2.5	0.73	3.44	< 0.001
(stand)	T1	8.4	62.22	0.14	0.89	6.4	62.22	0.10	0.92
	T2	10.4	114.54	0.09	0.93	8.9	114.54	0.08	0.94
	V1	-18.0	0.00	-15.99	0.00 *	-2.5	1.24	-2.04	0.04 *
	V2	-0.2	1.48	-0.15	0.88	-0.7	1.31	-0.56	0.57

[a]Reference levels for head position (i.e., 0 = tucked, 1 = down, or 2 = up) and head tilt (i.e., 0 = no tilt, 1 = slight tilt, or 2 = severe tilt) were each set at 0.

*Significant differences detected by the best-fit model ($P \leq 0.05$).

Table 2.8. Model selection results from generalized linear mixed model analysis of behavior (i.e., 1 = present or 0 = absent) of white-tailed deer fawns wearing GPS collars and uncollared fawns during the first 4 weeks of life for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020. We used Akaike's Information Criterion (AIC) to determine the best-fit model for each candidate set. Shown are number of parameters (*K*), Akaike's Information Criteria for small sample sizes (AIC_c), differences among AIC_c (ΔAIC), AIC_c weights (ω_i), and cumulative AIC_c weights (CumWt).

Behavior	Model	*K*	AIC_c	ΔAIC	ω_i	CumWt.
Vigilance	Collar	6	545.63	0.00	0.46	0.46
	Collar + sex	7	547.07	1.44	0.22	0.68
	Collar × week	11	547.73	2.11	0.16	0.84
	Collar + week + sex	8	549.05	3.43	0.08	0.92
	Collar × week + sex	12	549.24	3.62	0.08	1.00
Sleeping	Collar	6	565.71	0.00	0.47	0.47
	Collar + sex	7	566.60	0.89	0.30	0.76
	Collar + week + sex	8	568.67	2.96	0.11	0.87
	Collar × week	11	569.24	3.53	0.08	0.95
	Collar × week + sex	12	570.22	4.50	0.05	1.00
Locomotion	Collar	6	145.40	0.00	0.52	0.52
	Collar + sex	7	146.41	1.01	0.31	0.83
	Collar + week + sex	8	147.89	2.49	0.15	0.98
	Collar × week	11	153.27	7.87	0.01	0.99
	Collar × week + sex	12	154.33	8.93	0.01	1.00
Suckling	Collar	6	119.31	0.00	0.63	0.63
	Collar + sex	7	121.05	1.73	0.26	0.90
	Collar + week + sex	8	123.08	3.77	0.10	0.99

	Collar × week	11	128.45	9.13	0.01	1.00
	Collar × week + sex	12	130.24	10.93	0.00	1.00
Groomed	Collar + sex	7	113.50	0.00	0.52	0.52
	Collar	6	114.78	1.28	0.28	0.80
	Collar + week + sex	8	115.57	2.07	0.19	0.99
	Collar × week + sex	12	121.60	8.10	0.01	0.99
	Collar × week	11	122.75	9.25	0.01	1.00
Grooming	Collar	6	124.44	0.00	0.50	0.50
	Collar + sex	7	125.15	0.71	0.35	0.86
	Collar + week + sex	8	127.21	2.77	0.13	0.98
	Collar × week	11	132.35	7.91	0.01	0.99
	Collar × week + sex	12	133.11	8.66	0.01	1.00

Table 2.9. Behavioral differences (e.g. vigilance, sleeping, etc.) between white-tailed deer fawns wearing GPS collars (i.e., Telonics v1.0 [T1]; Telonics v2.0 [T2]; Vectronic v1.0 [V1]; Vectronic v2.0 [V2]) and uncollared fawns (UC [i.e., reference level]) for the first 4 weeks of life, based on mean estimates from the best-fit generalized linear mixed model for each candidate set for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020. Shown are regression coefficients (β), standard error (SE), *Z*-scores, and *P*-values.

Behavior	Collar	β	SE	*Z*	*P*
Vigilance	UC	0.4	0.17	2.35	0.019
	T1	-0.7	0.45	-1.65	0.098
	T2	-1.0	0.27	-3.61	< 0.001 *
	V1	-1.5	0.34	-4.37	< 0.001 *
	V2	-2.0	0.30	-6.61	< 0.001 *
Sleeping	UC	-1.0	0.19	-5.05	< 0.001
	T1	0.6	0.45	1.35	0.176
	T2	1.1	0.27	3.91	< 0.001 *
	V1	1.3	0.32	3.99	< 0.001 *
	V2	2.1	0.28	7.36	< 0.001 *
Locomotion	UC	-3.3	0.46	-7.24	< 0.001
	T1	1.3	0.77	1.76	0.078
	T2	0.1	0.68	0.14	0.887
	V1	-0.8	1.11	-0.71	0.480
	V2	-0.4	0.74	-0.50	0.620
Suckling	UC	-3.1	0.42	-7.44	< 0.001
	T1	-23.7	7.08	-0.03	0.974
	T2	-0.4	0.72	-0.54	0.587

	V1	-1.0	1.09	-0.89	0.373
	V2	-1.0	0.83	-1.18	0.240
Groomed	UC	-4.8	0.89	-5.36	< 0.001
	T1	0.8	1.18	0.68	0.498
	T2	0.0	0.93	0.00	0.997
	V1	0.7	0.94	0.74	0.460
	V2	0.1	0.83	0.07	0.944
Grooming	UC	-3.8	0.58	-6.55	< 0.001
	T1	-30.6	0.94	-0.17	1.000
	T2	-0.1	0.92	-0.10	0.922
	V1	1.8	0.71	2.54	0.101
	V2	-0.3	0.92	-0.28	0.781

*Significant differences detected by the best-fit model ($P \leq 0.05$).

Table 2.10. Number of occurrences of irregular behaviors for white-tailed deer fawns wearing GPS collars (i.e., Telonics v1.0 [T1]; Telonics v2.0 [T2]; Vectronic v1.0 [V1]; Vectronic v2.0 [V2]) during the first 4 weeks of life for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020.

	High-stepping		Forelimb restraint	
Collar	Fawns	Occurrences	Fawns	Occurrences
T1	2 of 6	10	2 of 6	2
T2	3 of 10	8	4 of 10	7
V1	12 of 20	17	1 of 20	1
V2	7 of 10	14	3 of 10	3

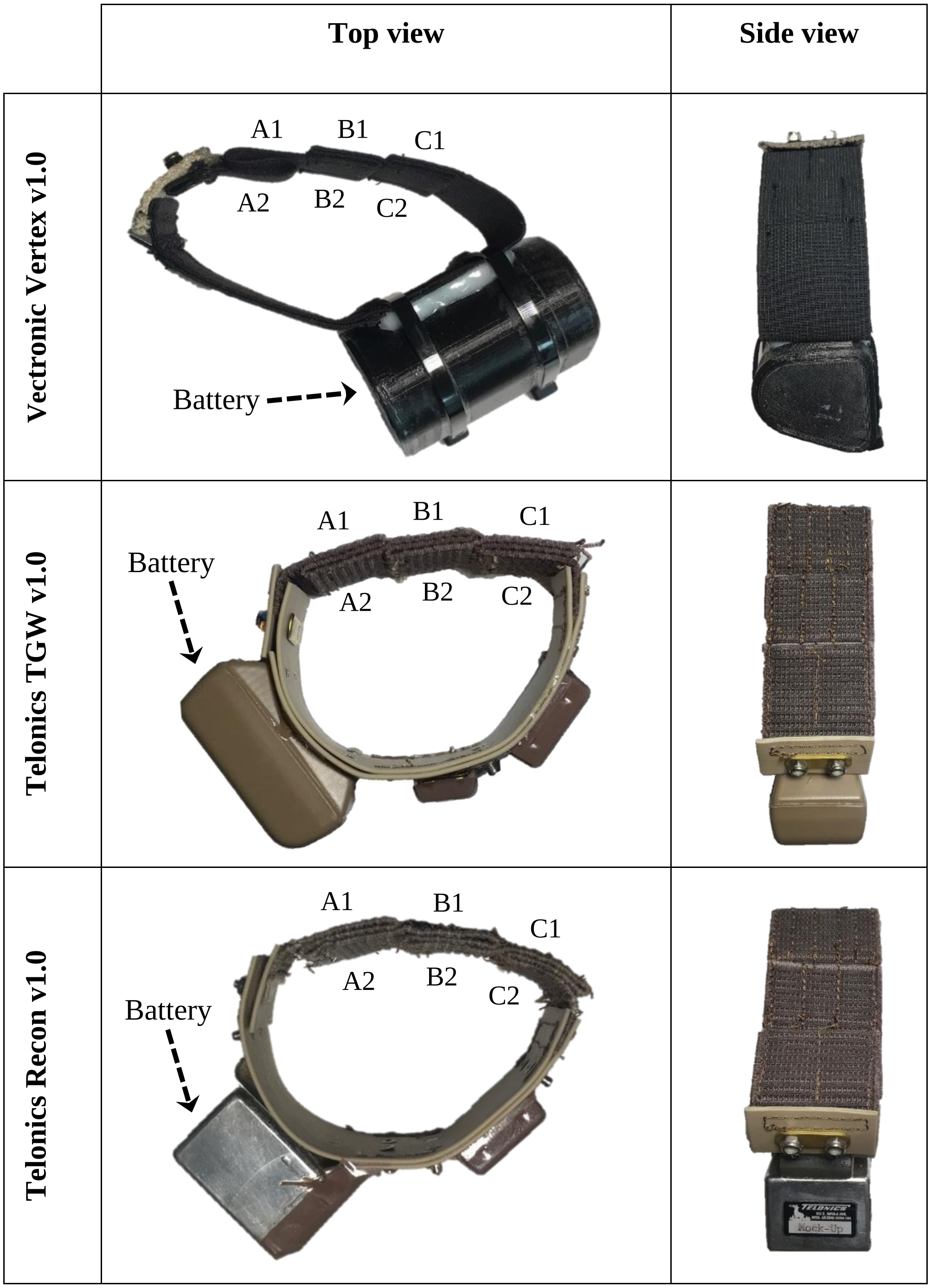

Figure 2.1. Vectronic Vertex v1.0 (V1), Telonics TGW v1.0 (T1), and Telonics Recon v1.0 (T1) collars deployed on white-tailed deer fawns for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019.

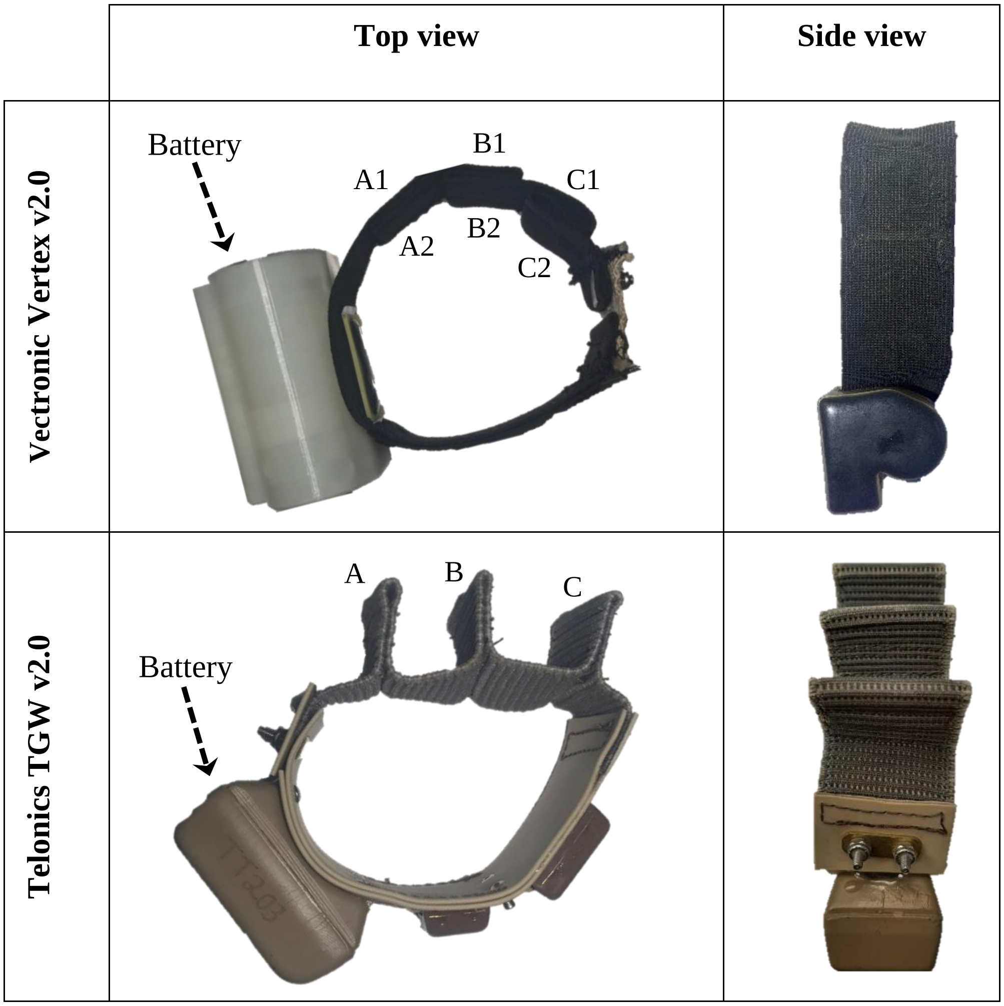

Figure 2.2. Vectronic Vertex v2.0 (V2) and Telonics TGW v2.0 (T2) collars deployed on white-tailed deer fawns for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2019–2020.

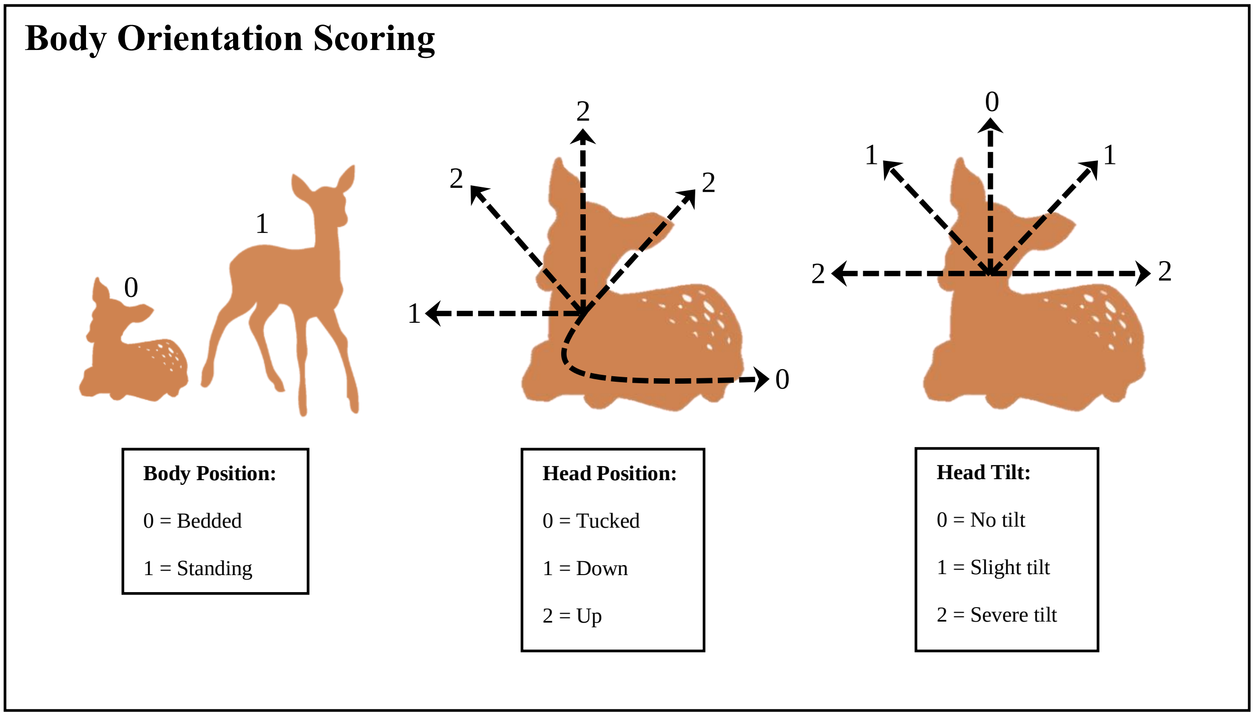

Figure 2.3. System used for recording body orientation of white-tailed deer fawns during behavioral observations in the outdoor paddocks, including scores of body position, head position, and head tilt for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020.

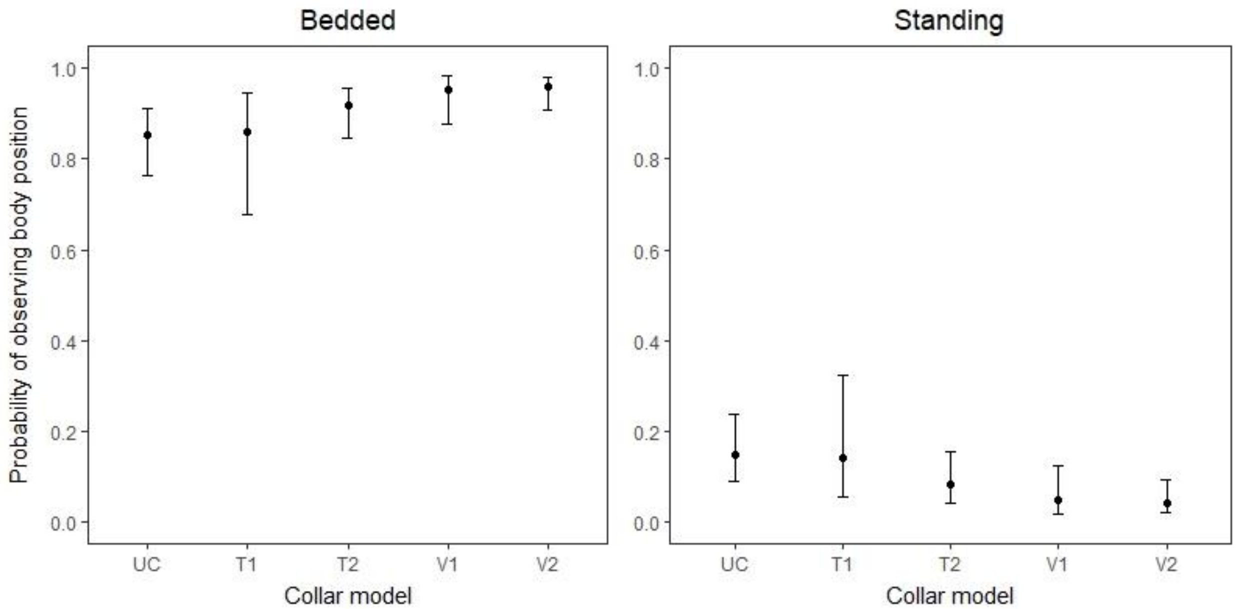

Figure 2.4. Probability of observing a bedded or standing white-tailed deer fawn for uncollared (UC) fawns and fawns wearing GPS collars (i.e., Telonics v1.0 [T1]; Telonics v2.0 [T2]; Vectronic v1.0 [V1]; Vectronic v2.0 [V2]) during the first 4 weeks of life, for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020. Vertical lines indicate the 95% CI for each estimate.

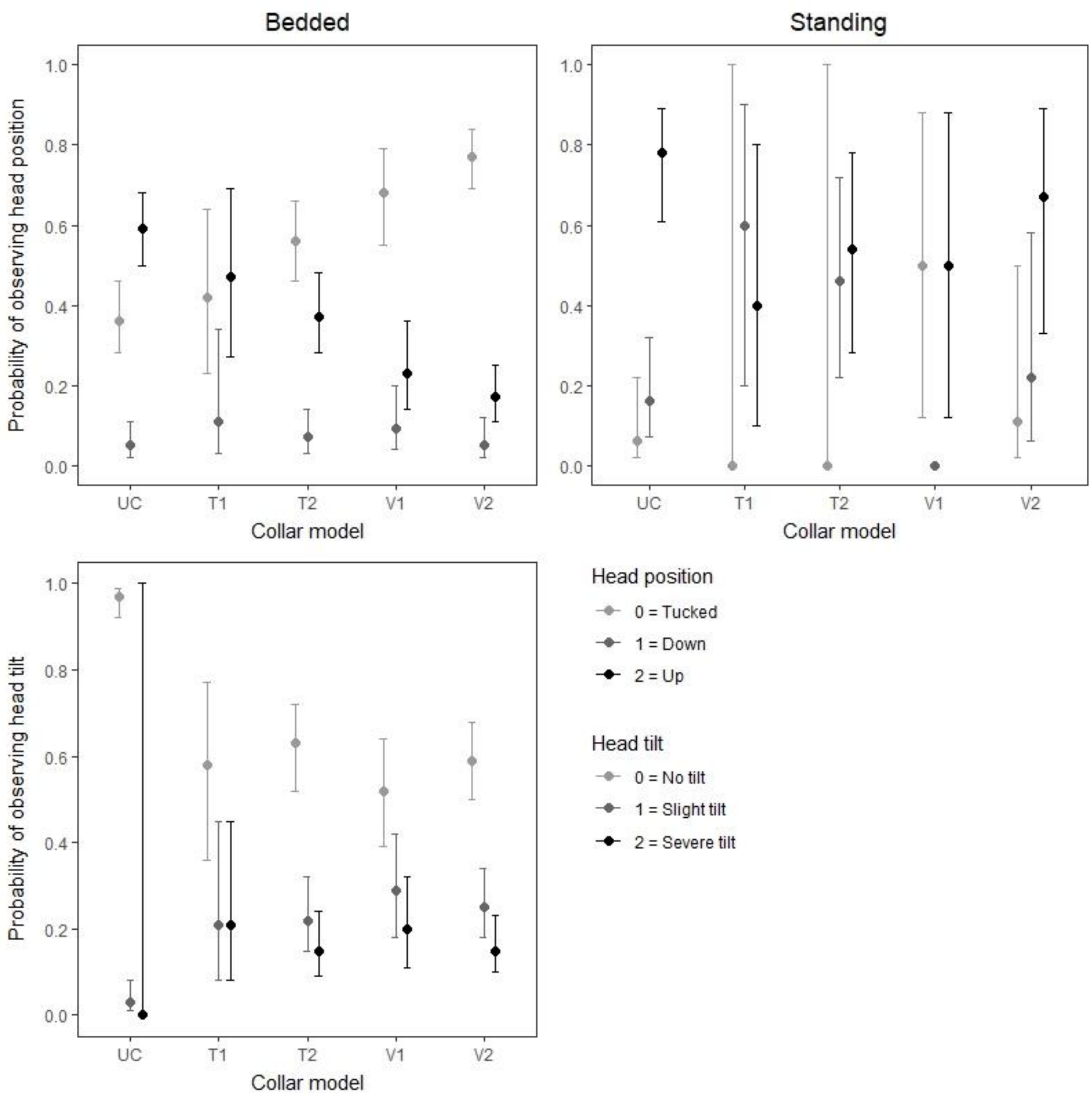

Figure 2.5. Probability of observing head positions and head tilt of uncollared (UC) white-tailed deer fawns and fawns wearing GPS collars (i.e., Telonics v1.0 [T1]; Telonics v2.0 [T2]; Vectronic v1.0 [V1]; Vectronic v2.0 [V2]) during the first 4 weeks of life, for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020. Vertical lines indicate the 95% CI for each estimate.

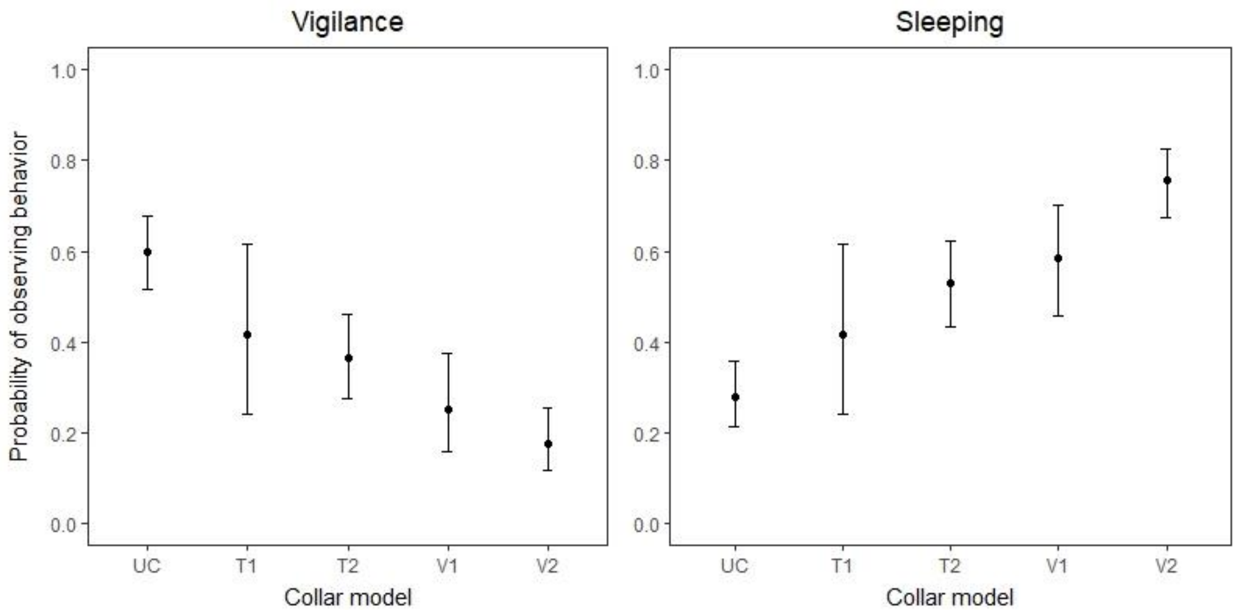

Figure 2.6. Probability of observing a vigilant or sleeping white-tailed deer fawn for uncollared (UC) fawns and fawns wearing GPS collars (i.e., Telonics v1.0 [T1]; Telonics v2.0 [T2]; Vectronic v1.0 [V1]; Vectronic v2.0 [V2]) during the first 4 weeks of life, for testing of expandable GPS collar mock-ups at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2020. Vertical lines indicate the 95% CI for each estimate.

CHAPTER 3

PREFERENCES OF CAPTIVE WHITE-TAILED DEER FOR ACORN SPECIES OF THE SOUTHEASTERN U.S.[1]

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ABSTRACT Oak (*Quercus* spp.) acorns are a seasonally important food source for white-tailed deer (*Odocoileus virginianus*) throughout much of their range. Preferential consumption of some acorn species over others could affect oak regeneration. We conducted cafeteria-style feeding preference trials with captive adult deer at Whitehall Deer Research Facility, Athens, GA, USA to evaluate preferential consumption by white-tailed deer of acorn species native to southeastern coastal environments (i.e., laurel oak, *Q. laurifolia*, live oak, *Q. virginiana*, sand live oak, *Q. geminata*, and water oak, *Q. nigra*) and southeastern mountain and piedmont environments (i.e., chestnut oak, *Q. montana*, northern red oak, *Q. rubra*, water oak, and white oak, *Q. alba*). We also evaluated acorn samples for nutritional composition. Mean (±SE) preferences indicated the following ranking (i.e., from most to least preferred) for acorns during coastal group trials: sand live oak ($\bar{x}$ = 0.32 ± 0.02), live oak ($\bar{x}$ = 0.31 ± 0.02), water oak ($\bar{x}$ = 0.19 ± 0.02), laurel oak ($\bar{x}$ = 0.11 ± 0.02). Mean preferences indicated the following ranking for acorns during mountain group trials: white oak ($\bar{x}$ = 0.41 ± 0.02), chestnut oak ($\bar{x}$ = 0.31 ± 0.02), water oak ($\bar{x}$ = 0.15 ± 0.01), and northern red oak ($\bar{x}$ = 0.09 ± 0.02). Deer preferred acorns lower in tannins, gross energy, crude fat, ADF, NDF, and ADL and acorns higher in crude protein, potassium, and phosphorus during feeding trials. Results of this study may help managers identify differences in selective consumption of acorns by deer and provide baseline information for future research investigating oak regeneration and deer behavior in the Southeast.

KEY WORDS acorns, food preferences, nutrition, oaks, *Odocoileus virginianus*, *Quercus* spp., southeastern United States, white-tailed deer.

INTRODUCTION

Oak (*Quercus* spp.) acorns are an important fall and winter food source of white-tailed deer (*Odocoileus virginianus*) throughout much of their range (McShea 2000, Haas and Heske 2005, McShea et al. 2007, Campbell and Wood 2013). Acorn production directly influences the movement, behavior, habitat use, and population sizes of white-tailed deer in portions of the southeastern United States (Miller et al. 1987, Wentworth et al. 1992, McShea et al. 2007). For example, deer in Virginia, USA spend approximately 40% of their time feeding in forest stands composed primarily of oaks during the fall in years of above-average acorn production as opposed to <5% during years of below average acorn production (McShea and Schwede 1993, McShea et al. 2007). There is growing concern for declines of oak abundance, and the associated influences on wildlife species, ecosystem function, timber industry, and conservation of iconic species (McShea et al. 2007, MacDougall et al. 2010, Holoubek and Jensen 2016). The causes of these declines are often unknown. However, recent studies have suggested declines may be attributed to changes in forest management practices, introduced diseases and pest species, or even changes in climate (Fei et al. 2011). Some oak species are less tolerant of disturbance than others. For example, white oak (*Q. alba*), with acorns highly preferred by white-tailed deer, grows more slowly and is more susceptible to catastrophic disturbances than other eastern oak species (Abrams 2003). Selective consumption by deer has exacerbated existing declines of vulnerable oak species (e.g., white oak) in parts of the eastern United States (Whitney 1994, Abrams 2003). Significant reductions in oak abundance likely would have detrimental effects on white-tailed deer populations in areas like the Southern Appalachians, where acorns are highly valued during the dormant season (Haas and Heske 2005, McShea et al. 2007). Evaluations of preferential consumption of oak acorn species native to the southeastern United States could provide insights into food selection of deer and provide baseline information for future studies investigating oak regeneration and deer behavior.

Previous studies have evaluated food preferences of wildlife using direct and indirect observations in the field (Crawford 1982, Parker et al. 1999, Verheyden-Tixier et al. 2008). However, field observations of animals feeding can be problematic as observers may be unable to accurately estimate food intake from a distance. Rumen or fecal content analysis and browse surveys commonly are used to assess feeding habits of large herbivores (Puglisi et al. 1978, Verme and Ullrey 1984, Dostaler et al. 2011). However, these methods often produce biased estimates of food preferences by not accounting for differences in food digestibility and availability (Verme and Ullrey 1984, Dostaler et al. 2011). Preference studies conducted in more controlled settings (e.g., captive research facilities) allow for detailed observation of animals and their selection of food items. Feeding trials conducted in controlled settings can also eliminate the potential effects of competition and predation, which can impact preferences by interrupting foraging bouts (Stephens and Krebs 1986, Scott and Provenza 2000, Dostaler et al. 2011). Conducting cafeteria-style feeding trials in a captive setting enables researchers to present animals with equal amounts of different foods and eliminates concerns with digestibility (Dostaler et al. 2011).

Acorns vary in chemical composition by group (e.g., white oak group, red oak group) and among species, and likely differ in nutritional value for white-tailed deer compared to other acorn-consuming mammals (Briggs and Smith 1989, Servello and Kirkpatrick 1989, Kirkpatrick and Pekins 2002, Vinha et al. 2016). For example, white oak acorns tend to be slightly lower in crude protein compared to red oak acorns; however, the inverse may be true in some instances (Briggs and Smith 1989, Servello and Kirkpatrick 1989). Acorns of the red oak group often are higher in crude fat compared to white oak acorns, and there is a positive correlation between crude fat and gross energy of acorns (Briggs and Smith 1989, Servello and Kirkpatrick 1989, Smallwood et al. 2001, Kirkpatrick and Pekins 2002). However, higher presence of phenolics (e.g., tannins) in acorns may decrease the overall nutritional value (Servello and Kirkpatrick 1989). Tannins are known to interfere with digestion of proteins and reduce palatability of forage (Servello and Kirkpatrick 1989, Kirkpatrick and Pekins 2002). Acorns of the white oak group, which are most often lower in tannins, are typically preferred by acorn-consuming mammals compared to red oak acorns (Servello and Kirkpatrick 1989, Johnson et al. 1993, Smallwood et al. 2001, Kirkpatrick and Pekins 2002). Characterization of nutritional components (e.g., gross energy, tannins, macronutrients, detergent fiber, lignin, ash, minerals, etc.) for oak acorns native to the southeastern United States may help provide a better understanding of potential relationships between chemical composition of foods and deer diet selection.

We conducted a series of cafeteria-style feeding preference trials with captive adult deer and evaluated acorn samples for nutritional composition. Our objectives were to: 1) evaluate preferential consumption by white-tailed deer of acorn species native to the southeastern United States, and 2) characterize the nutritional composition of those acorns. We hypothesized that deer would prefer oak acorns of the white oak group over red oak acorns, and that deer would prefer to consume acorns lower in tannins (e.g., acorns which are more palatable and easier to digest) during feeding trials. Additionally, we expected deer to select acorns lower in crude protein, crude fat, and gross energy based on previously observed relationships between oak acorn groups and nutrient composition.

METHODS

Study Site

We conducted our study with captive white-tailed deer at the Whitehall Deer Research Facility on the University of Georgia campus in Athens, GA, USA (83°21'13.0"W, 33°53'18.7"N). The facility is approximately 2.4 ha surrounded by 3-m-high woven-wire fencing. We housed captive deer in 0.4–0.8-ha outdoor paddocks (12–14 adult deer each) and 3 × 6-m covered barn stalls. We provided deer with pelleted feed (Purina AntlerMax Deer Breeder Textured 17-6, Gainesville, GA, USA), perennial peanut hay, and water *ad libitum* prior to them participating in feeding trials. All methods were approved by the University of Georgia Institutional Animal Care and Use Committee under Animal Use Proposal A2018 08-024-Y1-A0.

Animal Handling

Before deer participated in acorn preference trials, we held them in outdoor paddocks where they were fed as described above. We moved 6 deer from outdoor paddocks into individual barn stalls 4 days before the start of preference trials. We housed deer in 3 × 6 m barn stalls for a total of 9 days to familiarize them with the feeding protocol and to conduct acorn preference trials. Once trials concluded, we moved deer from barn stalls back to the outdoor paddocks.

Feeding Trials

Acorns used in our study were collected fresh by a regional supplier (Urban Forestry Services, Micanopy, Florida, USA) from trees or immediately following acorn drop. We stored acorns frozen, limited freezer access, and conducted trials in a timely manner to prevent germination and decomposition. We weighed and thawed acorns at room temperature before each trial. We handled acorns, feeding trays, and partitioned feeding troughs with clean, disposable latex gloves to minimize human scent contamination.

We conducted cafeteria-style feeding trials on 6 adult female deer using two separate acorn trial groups: a coastal oak group and a mountain (i.e., including piedmont species) oak group. The coastal group consisted of laurel oak (*Q. laurifolia*), live oak (*Q. virginiana*), sand live oak (*Q. geminata*), and water oak (*Q. nigra*) acorns. The mountain group consisted of chestnut oak (*Q. montana*), northern red oak (*Q. rubra*), water oak, and white oak acorns. We conducted 20 feeding trials during 2 seasons (i.e., 10 late fall trials and 10 early winter trials) using each acorn group (i.e., 5 coastal group trials and 5 mountain group trials per season). We selected tame (i.e., bottle-weaned) deer to minimize potential impacts of handling and confinement in barn stalls. Deer at the facility readily consume water oak acorns in the outdoor paddocks. To familiarize deer with the feeding protocol, we allowed them to eat water oak acorns from 4 separate feeding trays within a partitioned trough placed on the floor in the center of their stall for 3 days before the start of feeding trials. After deer became familiar with eating acorns from the troughs, they participated in a feeding trial during each of the next 5 days. We restricted access to feed for 12 hr immediately before each preference trial. Each trial consisted of 3 consecutive intervals of 30-min duration for a total of 90 min of observation. At each interval, we introduced 75 g of each acorn species from the specified acorn group to each deer. We removed and weighed each acorn species at 30, 60 and 90 min of elapsed time, and recorded residual mass (g). After weighing, we replenished each species to 75 g before reintroducing the feeding tray to deer. At the end of trials, we reintroduced pelleted feed and hay until 0500 EST of the following morning. We conducted all feeding trials and pre-trial training from 1700–1830

EST each day. To minimize cross-contamination of acorn scents, we rinsed compartments of the feeding tray with water and dried them with paper towels. To minimize bias of a deer preferring to feed in a specific location within the barn stall, we rotated acorn species one place clockwise in the feeding tray between sessions.

Nutritional Analysis

We submitted a sample of each acorn species used in feeding trials to the Washington State University Wildlife Habitat and Nutrition Laboratory in Pullman, Washington, USA for chemical nutritional analysis during 2019. Gross energy (kcal/g) values were obtained using bomb calorimetry, a standard method for measuring calorific values of plant material (Wasserman and Chapman 2003). Crude fat, crude protein, neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), acid insoluble ash (AIA), calcium (Ca), magnesium (Mg), phosphorus (P), and potassium (K) were reported as a percentage of oven-dry matter. We derived tannin concentrations (% dry weight) for acorn species from prior literature (Table 3.1).

Data Analysis

We analyzed data using program R 4.0.3 (R Core Team 2020). We plotted the percentage of each acorn species consumed at each interval (*Y*-axis) against time at each weighing (*X*-axis, i.e., at 0, 30, 60 and 90 minutes) for each trial, then calculated the area under each curve using the area under curve (AUC) function in Program R (Rodgers 1990, Johannessen and Samset 1994, Suarez and Kravetz 1998, Dostaler et al. 2011). We compared acorn species for each trial by dividing the AUC of each species by the sum of all AUCs in a trial to obtain a unit-less index ranging between 0 (i.e., avoided) and 1 (i.e., preferred). We analyzed the preference indices of acorn species using generalized linear mixed models (GLMMs) with acorn species (reference level = water oak [i.e., control]) as the independent variable, season (i.e., fall or winter) and trial number (i.e., Trial 1, Trial 2, etc.) as covariates, and deer identification as a random factor. We used Akaike's Information Criterion (AIC) to determine the best-fit model. We used Spearman's rank correlation coefficients and plotted mean preference indices (*Y*-axis) against components of nutritional analysis (*X*-axis) to determine potential relationships. We compared tannin concentrations reported in prior studies to preference indices of acorn species offered during feeding preference trials (Table 3.1). Tannin concentrations for willow and water oak acorns were used to represent laurel oak due to the hybrid nature of the species (Burk 1963).

RESULTS

The best-fit model for preference indices by acorn species included season as a covariate and deer identification as a random factor (AIC_c = -285.50, Table 3.2). Mean preferences indicated the following ranking (i.e., from most to least preferred) for acorns during coastal group trials: sand live oak ($\bar{x}$ = 0.32 ± 0.02), live oak ($\bar{x}$ = 0.31 ± 0.02), water oak ($\bar{x}$ = 0.19 ± 0.02), laurel oak ($\bar{x}$ = 0.11 ± 0.02; Table 3.2). Mean preferences indicated the following ranking (i.e., from most to least preferred) for acorns during mountain group trials: white oak ($\bar{x}$ = 0.41 ± 0.02), chestnut oak ($\bar{x}$ = 0.31 ± 0.02), water oak ($\bar{x}$ = 0.15 ± 0.01), and northern red oak ($\bar{x}$ = 0.09 ± 0.02; Table 3.2). Deer preferred acorns belonging to the white oak group (i.e., chestnut oak, live oak, sand live oak, and white oak) compared to those of the red oak group (i.e., laurel oak, northern red oak, and water oak) during feeding trials (Table 3.2).

There was a negative relationship between preference of acorns during mountain group trials and tannin concentrations reported in prior studies (Table 3.1, Fig 3.1). No significant correlation ($P > 0.05$) was detected between preference of acorns during coastal group trials and tannin concentrations reported in prior studies (Table 3.1, Fig 3.1); although, the most preferred acorns (i.e., live oaks) were reported to be generally lower in tannins. Deer preferred acorns lower in gross energy, crude fat, ADF, NDF, and ADL during feeding trials (Fig 3.2–3.5). Deer preferred acorns higher in crude protein (Fig 3.3), potassium (Fig 3.6), and phosphorus (Fig 3.7) during feeding trials. No significant correlation ($P < 0.05$) was detected between preference and AIA of acorns during feeding trials (Fig 3.5). Deer preferred acorns lower in calcium during coastal group trials, while deer in mountain group trials generally selected acorns higher in calcium (Fig 3.6). Deer preferred acorns higher in magnesium during coastal group trials, while deer in mountain group trials generally selected acorns lower in magnesium (Fig 3.7).

DISCUSSION

Deer most preferred acorns of the white oak group (i.e., chestnut, live, sand live, and white oak) compared to acorns of the red oak group (i.e., laurel, northern red, water) during feeding trials, which was expected based on the available literature surrounding preferential consumption of oak acorns by deer. If each of these acorn species are available simultaneously in environments, our findings suggest deer may more readily select white oak acorns over red oak acorns. Temporal availability of acorns varies by species, thus more preferred species in captive trials are not necessarily the most valued by wild deer. For example, white oak acorns (i.e., preferred species) drop in early fall, while red oak acorns generally drop several weeks later (Smallwood et al. 2001). However, red oak acorns are often available to deer throughout the winter (i.e., when resources are most limited) compared to white oak acorns, which germinate in the fall (Smallwood et al. 2001). We also recognize that food preferences of captive deer may differ from wild deer, which are accustomed to different diets and learned behaviors. The primary limitation of cafeteria-style feeding trials is that captive deer are presented with equal availability of each forage, which is not true representation of how wild deer select forage in their environment. Availability of various food items may differ substantially across a landscape and will depend on numerous factors including climate, elevation, soil quality, and competition (Goodrum et al. 1971, Haas and Heske 2005). Wild deer also expend time and energy traveling distances to acquire forage, which may require some level of intrinsic cost-benefit analysis (i.e., optimal foraging) when searching for quality forage (Hanley 1997, Berteaux et al. 1998). Results of this study only provide a baseline for understanding deer selection of acorns native to the southeastern United States, and further research is warranted to assess preferences of wild deer for acorns in these regions.

As expected, deer preferred acorns reported in prior studies to be lower in tannins (i.e., white oaks), as these acorns were likely more palatable and more easily digested compared to acorns reported to be higher in tannins (i.e., red oaks). Gross energy and crude fat were positively related, as high fat content indicates a greater energy content (Servello and Kirkpatrick 1989). Acorn species more preferred by deer were generally lower in gross energy and crude fat during coastal and mountain group trials, consistent with prior literature (Briggs and Smith 1989, Servello and Kirkpatrick 1989, Smallwood et al. 2001, Kirkpatrick and Pekins 2002). The positive correlations between preference and crude protein were unexpected based on prior reports indicating white oak acorns are generally lower in protein; however, protein content of red oaks have been reported to be lower in some instances (Briggs and Smith 1989, Servello and Kirkpatrick 1989). Neutral detergent fiber (NDF) and acid detergent fiber (ADF) are measures of forage bulkiness which often share a negative correlation with digestibility and preference (Dykes et al. 2020). Normally, measurements of NDF and ADF are positively correlated with acid detergent lignin (ADL, Dostaler et al. 2011). Therefore, it is expected that red oak acorns are commonly higher in these values. We observed similar trends between preference and NDF, ADF, and ADL of oak acorns during coastal and mountain group trials. Acorns of the white oak group often are higher in acid insoluble ash (AIA) compared to red oak acorns, exhibiting a positive relationship between AIA and preference (Briggs and Smith 1989); however, we detected no correlations. Mineral content (e.g., calcium, magnesium, and phosphorus) in diets of white-tailed deer has been shown to be lower during the dormant season compared to much of the growing season (Jones and Weeks 1985); however, little literature is available discussing relationships between preference and mineral levels among acorns.

Physiological needs of large herbivore species vary seasonally; therefore, white-tailed deer may increase or decrease intakes of protein and digestible energy based on their current or prospective needs (Berteaux et al. 1998, Dostaler et al. 2011). We detected no seasonal variation (i.e., fall and winter) in preferences of acorns; however, we recommend future studies conduct acorn feeding trials across a longer period of time (e.g., starting in the fall and further into the winter months) to develop a more comprehensive understanding of seasonal acorn selection by deer. Seasonal availability and germination of various oak acorn species would be important considerations when selecting acorns for feeding trials over an extended period of time. Additionally, nutritional analyses of these acorns at multiple intervals across time (i.e., seasonally) could allow for modeling of preference indices in relation to acorn species and nutritional components over time.

MANAGEMENT IMPLICATIONS

Abundance and species composition of oaks is affected by forest-management practices and processes of oak regeneration. Preferential consumption of some acorns over others by deer could also affect establishment and characteristics of oak regeneration. The results of this study may help managers identify differences in selective consumption of acorns by deer and provide baseline information for future research investigating oak regeneration, deer diet selection, chemical composition of foods, and deer movement ecology, behavior, and habitat use in the southeastern United States. This research highlights the importance of considering differences in acorn preferences by deer when prescribing forest-management practices, although managers should continue to promote diversity of species to help buffer boom-or-bust production patterns among oaks.

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LITERATURE CITED

Abrams, M. D. 2003. Where has all the white oak gone? Bioscience 53:927–939.

Berteaux, D., M. Crete, J. Huot, J. Maltais, and J. P. Ouellet. 1998. Food choice by white-tailed deer in relation to protein and energy content of the diet: a field experiment. Oecologia 115:84–92.

Briggs, J. M., and K. G. Smith. 1989. Influence of habitat on acorn selection by *Peromyscus leucopus*. Journal of Mammalogy 70:35–43.

Burk, J. B. 1963. The hybrid nature of *Quercus laurifolia*. Journal of Elisha Mitchell Scientific Society 79:159–163.

Campbell, S. A. B., and T. C. Wood. 2013. Influences of precipitation, temperature, and acorn mast on white-tailed deer body weight in the Northern Piedmont of Virginia. Northeastern Naturalist 20:469–477.

Crawford, H. S. 1982. Seasonal food selection and digestibility by tame white-tailed deer in central Maine. Journal of Wildlife Management 46:974–982.

Dostaler, S., J. P. Ouellet, J. F. Therrien, and S. D. Cote. 2011. Are feeding preferences of white-tailed deer related to plant constituents? Journal of Wildlife Management 75:913–918.

Dykes, J. L., B. K. Strickland, S. Demarais, D. B. Reynolds, and M. A. Lashley. 2020. Diet selection of white-tailed deer supports the nutrient balance hypothesis. Behavioural Processes 179:104196.

Fei, S., N. Kong, K. C. Steiner, W. K. Moser, and E. B. Steiner. 2011. Change in oak abundance in the eastern United States from 1980 to 2008. Forest Ecology and Management 262:1370–1377.

Feldhamer, G. A., T. P. Kilbane, and D. W. Sharp. 1989. Cumulative effect of winter on acorn yield and deer body weight. Journal of Wildlife Management 53:292–295.

Goodrum, P. D., V. H. Reid, and C. E. Boyd. Acorn yields, characteristics, and management criteria of oaks for wildlife. Journal of Wildlife Management 35:520–532.

Haas, J. P., and E. J. Heske. 2005. Experimental study of the effects of mammalian acorn predators on red oak acorn survival and germination. Journal of Mammalogy 86:1015–1021.

Hanley, T. A. 1997. A nutritional view of understanding and complexity in the problem of diet selection by deer (Cervidae). Nordic Society Oikos 79:209–218.

Holoubek, N. S., and W. E. Jensen. 2016. Avian nest success along a habitat gradient in the Cross Timbers oak savanna. American Midland Naturalist 176:234–246.

Johannessen, V., and E. Samset. 1994. Summer diet of the mountain hare (*Lepus timidus* L.) in a low-alpine area in southern Norway. Canadian Journal of Zoology 72:652–657.

Johnson, W. C., L. B. Thomas, and C. S. Adkisson. 1993. Dietary circumvention of acorn tannins by blue jays. Oecologia 94:159–164.

Jones, R. L., and H. P. Weeks Jr. 1985. Ca, Mg, and P in the annual diet of deer in south-central Indiana. Journal of Wildlife Management 49:129-133.

Kirkpatrick, R. L., and P. J. Pekins. 2002. Nutritional value of acorns. Pages 173–181 *in* W. J. McShea and W. M. Healy, editors. Oak forest ecosystems. Johns Hopkins University Press, Baltimore, Maryland, USA.

Martin, A. C., H. C. Zim, and A. L. Nelson. 1961. American wildlife and plants: a guide to wildlife food habits. Dover Publications, New York, New York, USA.

MacDougall, A. S., A. Duwyn, and N. T. Jones. 2010. Consumer-based limitations drive oak recruitment failure. Ecological Society of America 91:2092–2099.

McShea, W. J., and G. Schwede. 1993. Variable acorn crops; responses of white-tailed deer and other mast consumers. Journal of Mammalogy 74:999–1006.

McShea, W. J. 2000. The influence of acorn crops on annual variation in rodent and bird populations. Ecological Society of America 81:228–238.

McShea, W. J., W. M. Healy, P. Devers, T. Fearer, F. H. Koch, D. Stauffer, and J. Waldon. 2007. Forestry matters: decline of oaks will impact wildlife in hardwood forests. Journal of Wildlife Management 71:1717–1728.

Miller, K. V., K. E. Kammermeyer, R. L. Marchington, and E. B. Moser. 1987. Population and habitat influences on antler rubbing by white-tailed deer. Journal of Wildlife Management 51:62–66.

Nelson, J. T., R. D. Slack, and G. F. Gee. 1996. Nutritional value of winter foods for whooping cranes. The Wilson Bulletin 108:728–739.

Ofcarcik, R. P., and E. E. Burns. 1971. Chemical and physical properties of selected acorns. Journal of Food Science 36:576–578.

Parker, K. L., M. P. Gillingham, T. A. Hanley, and C. T. Robbins. 1999. Energy and protein balance of free-ranging black-tailed deer in natural forest environment. Wildlife Monographs 143:3–48.

Puglisi, M. J., S. A. Liscinsky, and R. F. Harlow. 1978. An improved methodology of rumen content analysis for white-tailed deer. Journal of Wildlife Management 42:397–403.

Rodgers, A. R. 1990. Evaluating preference in laboratory studies of diet selection. Canadian Journal of Zoology 68:188–190.

Scott, L. L., and F. D. Provenza. 2000. Lambs fed protein or energy imbalanced diets forage in locations and on foods that rectify imbalances. Applied Animal Behavior Science 68:293–305.

Servello, F. A., and R. L. Kirkpatrick. 1989. Nutritional value of acorns for ruffed grouse. Journal of Wildlife Management 53:26–29.

Smallwood, P. D., M. A. Steele, and S. H. Faeth. 2001. The ultimate basis of the caching preferences of rodents, and the oak-dispersal syndrome: tannins, insects, and seed germination. American Zoology 41:840–851.

Smith, C. C., and D. Follmer. 1972. Food preferences of squirrels. Ecology 53:82–91.

Stephens, D. W., and J. R. Krebs. 1986. Foraging theory. Princeton University Press, Princeton, New Jersey, USA.

Suarez, O. V., and F. O. Kravetz. 1998. Transmission of food selectivity from mothers to offspring in *Akodon azarae* (Rodentia, Muridae). Behaviour 135:251–259.

Verheyden-Tixier, H., P. C. Renaud, N. Morellet, J. Jamot, J. M. Besle, and B. Dumont. 2008. Selection for nutrients by red deer hinds feeding on a mixed forest edge. Oecologia 156:715–726.

Verme, L. J., and D. E. Ullrey. 1984. Physiology and nutrition. Pages 91–118 *in* L. K. Halls, editor. White-tailed deer ecology and management. Stackpole Books, Harrisburg, Pennsylvania, USA.

Vinha, A. F., J. C. M. Barreira, A. S. G. Costa, and M. B. P. P. Oliveira. 2016. A new age for *Quercus* spp. fruits: review on nutritional and phytochemical composition and related biological activities of acorns. Comprehensive Reviews in Food Science and Food Safety 15:947–981.

Wasserman, M. D., and C. A. Chapman. 2003. Determinants of colobine monkey abundance: the importance of food energy, protein and fiber content. Journal of Animal Ecology 72:650–659.

Wentworth, J. M., A. S. Johnson, and P. E. Hale. 1992. Relationships of acorn abundance and deer herd characteristics in the Southern Appalachians. Southern Journal of Applied Forestry 16:5–8.

Whitney, G. G. 1994. From coastal wilderness to fruited plain. Cambridge University Press, Cambridge, United Kingdom.

Table 3.1. Tannin concentrations reported in prior studies characterizing nutritional composition of acorn species offered during coastal and mountain feeding preference trials at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019. Tannin concentrations for willow and water oak acorns were used to represent laurel oak due to the hybrid nature of the species.

Acorn species	Tannin concentration (% dry wt.)	Study[a]
Chestnut oak	8.1	4
Live oak	0.9–7.3	1, 5
Northern red oak	6.0–14.0	2, 3, 4, 6
Water oak	8.8	1
White oak	2.9–6.0	2, 4, 6
Willow oak	7.2	1

[a]1, Ofcarcik and Burns 1971; 2, Smith and Follmer 1972; 3, Briggs and Smith 1989; 4, Servello and Kirkpatrick 1989; 5, Nelson et al. 1996; 6, Smallwood et al. 2001

Table 3.2. Model selection results from a generalized linear mixed model analysis of preference indices (i.e., ranging from 0 = avoided to 1 = preferred) of adult female white-tailed deer for southeastern acorn species during feeding preference trials at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019. We used Akaike's Information Criterion (AIC) to determine the best-fit model. Shown are number of parameters (*K*), Akaike's Information Criteria for small sample sizes (AIC_c), differences among AIC_c (ΔAIC), AIC_c weights (ω_i), and cumulative AIC_c weights (CumWt).

Group	Model	*K*	AIC_c	ΔAIC_c	ω_i	CumWt
Coastal	Acorn + season	7	-285.50	0.00	0.74	0.74
	Acorn + trial	7	-283.38	2.12	0.26	1.00
	Acorn + season + trial	8	-274.87	10.64	0.00	1.00
	Acorn × season	10	-267.66	17.84	0.00	1.00
	Acorn + season × trial	9	-265.59	19.91	0.00	1.00
Mountain	Acorn + season	7	-379.05	0.00	0.74	0.74
	Acorn + trial	7	-376.93	2.12	0.26	1.00
	Acorn + season + trial	8	-368.04	11.01	0.00	1.00
	Acorn × season	10	-359.88	19.17	0.00	1.00
	Acorn + season × trial	9	-358.35	20.70	0.00	1.00

Table 3.3. Preferential differences (i.e., ranging from 0 = avoided to 1 = preferred) of adult female white-tailed deer for southeastern acorn species (reference level = water oak), based on mean estimates from the best-fit generalized linear mixed model (i.e., Preference ~ Acorn + Season) for feeding preference trials at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019. Shown are regression coefficients (β), standard error (SE), *Z*-scores, and *P*-values.

Group	Predictor	β	SE	*Z*	*P*
Coastal	Water oak	0.19	0.02	24.96	< 0.001
	Laurel oak	-0.08	0.02	-4.87	< 0.001 *
	Live oak	0.12	0.02	5.09	< 0.001 *
	Sand live oak	0.13	0.02	5.62	< 0.001 *
	Season (winter)	0.01	0.01	0.28	0.78
Mountain	Water oak	0.15	0.01	26.87	< 0.001
	Chestnut oak	0.16	0.02	9.27	< 0.001 *
	Northern red oak	-0.06	0.02	-4.04	< 0.001 *
	White oak	0.26	0.02	13.58	< 0.001 *
	Season (winter)	0.01	0.01	0.33	0.74

Table 3.4. Gross energy (kcal/g) and nutrient composition (i.e., crude fat, crude protein, neutral detergent fiber [NDF], acid detergent fiber [ADF], acid detergent lignin [ADL], acid insoluble acid [AIA], calcium, magnesium, phosphorus, and potassium) deer during feeding preference trials at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019.

Component	Chestnut	Laurel	Live	Northern red	Sand live	Water	White
Gross energy	4.66	5.51	4.90	5.29	4.80	5.71	4.66
Crude fat	9.79	20.44	12.26	14.41	6.54	24.05	11.61
Crude protein	6.19	3.31	7.30	4.77	6.67	4.30	5.23
NDF	24.57	36.82	25.73	34.75	26.22	40.20	34.54
ADF	15.27	25.69	14.42	23.83	14.60	26.03	22.54
ADL	3.68	14.05	6.69	7.91	6.21	13.57	7.24
AIA	0.14	0.16	0.16	0.20	0.15	0.27	0.37
Calcium	0.38	0.33	0.11	0.35	0.22	0.42	0.47
Magnesium	0.08	0.07	0.11	0.10	0.09	0.08	0.07
Phosphorus	0.08	0.05	0.07	0.06	0.08	0.05	0.07
Potassium	0.55	0.28	0.57	0.54	0.52	0.33	0.55

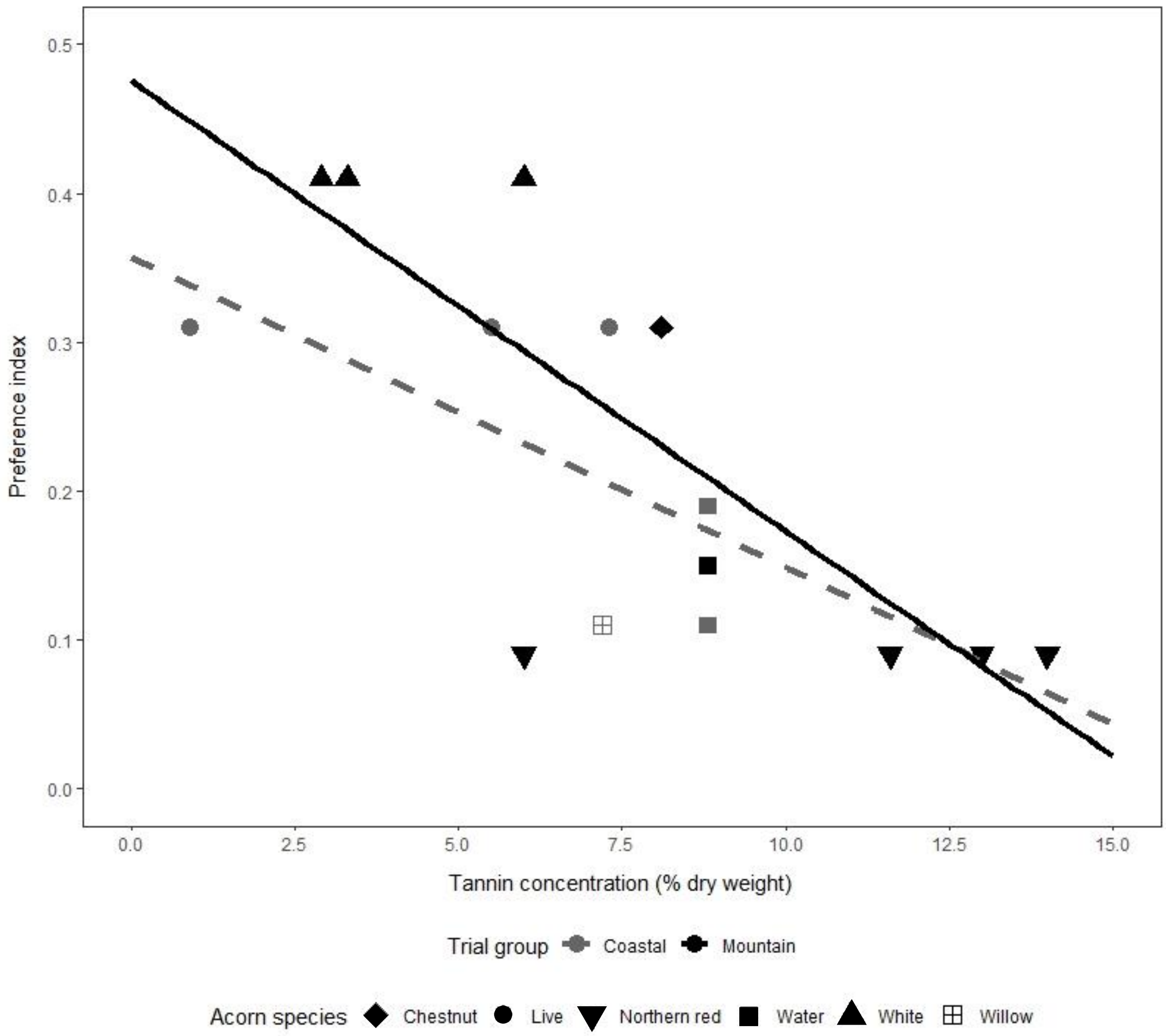

Figure 3.1. Mean preference indices (i.e., ranging from 0 = avoided to 1 = preferred) of adult female white-tailed deer in relation to tannin concentrations (coastal [$r_s = -0.58$, $P = 0.23$], mountain [$r_s = -0.79$, $P = 0.01$]) reported in prior studies characterizing nutrient composition of acorn species offered during coastal and mountain feeding preference trials at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019. Tannin concentrations for willow and water oak acorns were used to represent laurel oak due to the hybrid nature of the species.

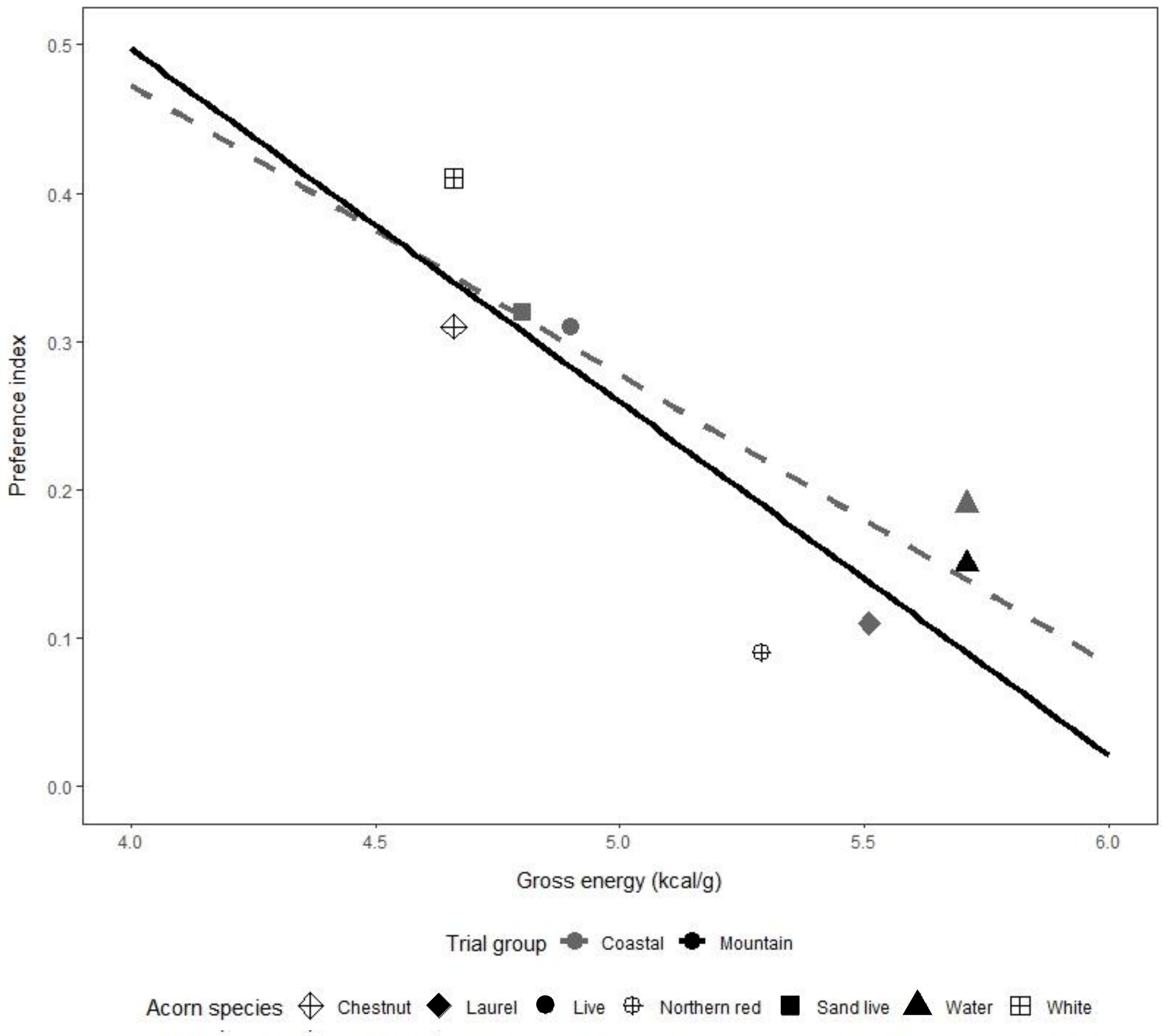

Figure 3.2. Mean preference indices (i.e., ranging from 0 = avoided to 1 = preferred) of adult female white-tailed deer in relation to gross energy (coastal [$r_s = -0.45$, $P < 0.001$], mountain [$r_s = -0.68$, $P < 0.001$]) for acorns offered during feeding preference trials at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019.

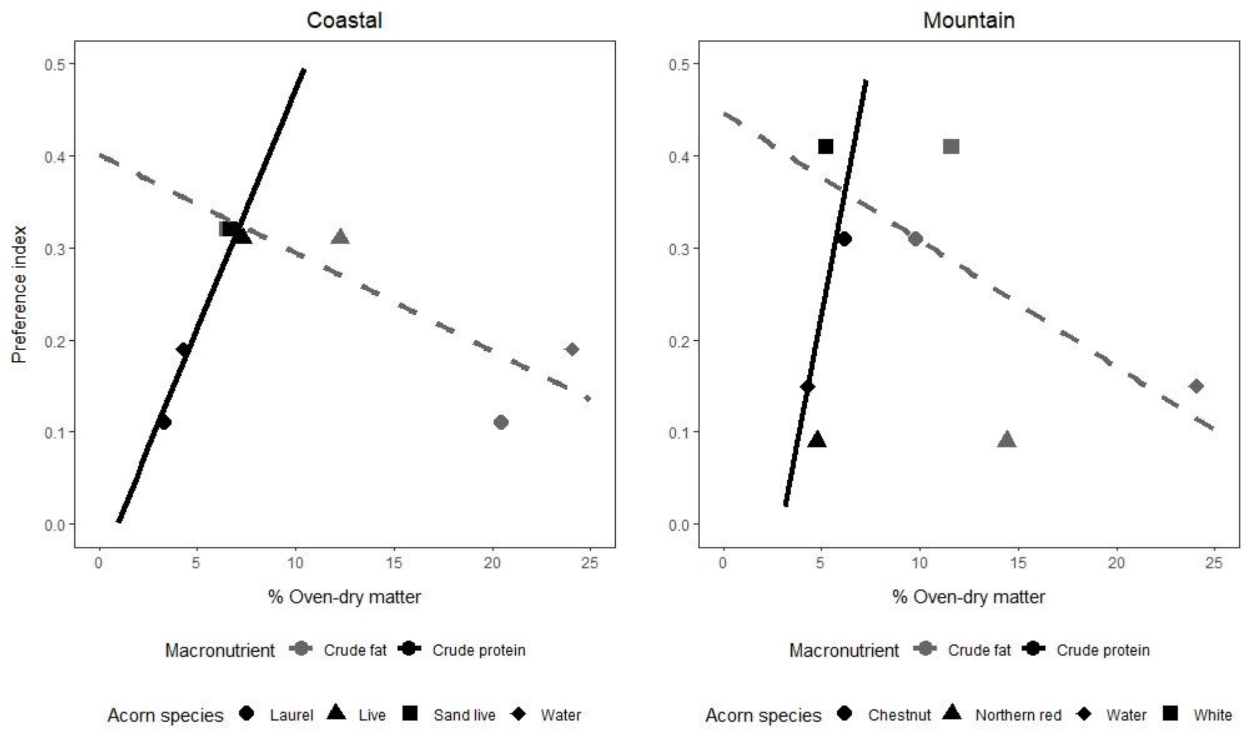

Figure 3.3. Mean preference indices (i.e., ranging from 0 = avoided to 1 = preferred) of adult female white-tailed deer in relation to crude fat (coastal [$r_s = 0.58$, $P < 0.001$], mountain [$r_s = 0.57$, $P < 0.001$]) and crude protein (coastal [$r_s = -0.45$, $P < 0.001$], mountain [$r_s = -0.57$, $P < 0.001$]) for acorns offered during feeding preference trials at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019.

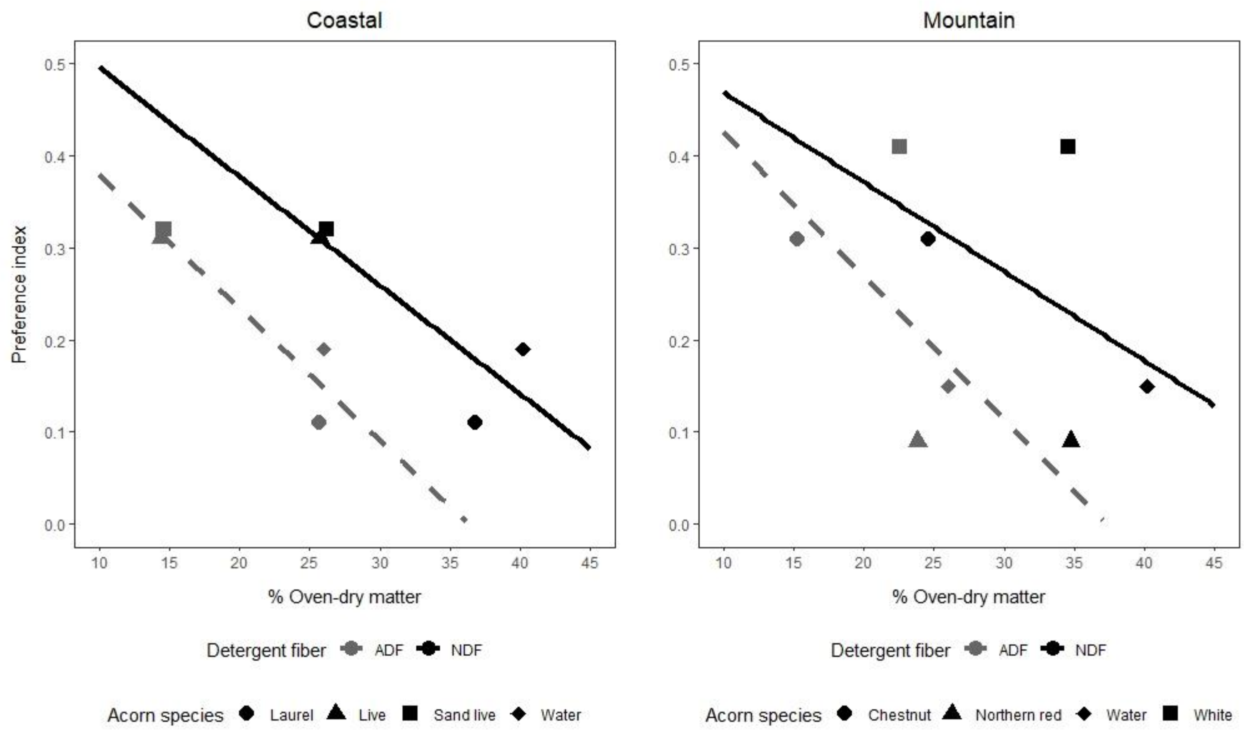

Figure 3.4. Mean preference indices (i.e., ranging from 0 = avoided to 1 = preferred) of adult female white-tailed deer in relation to acid detergent fiber (ADF; coastal [$r_s = -0.43$, $P < 0.001$], mountain [$r_s = -0.57$, $P < 0.001$]) and neutral detergent fiber (NDF; coastal [$r_s = -0.43$, $P < 0.001$], mountain [$r_s = -0.57$, $P < 0.001$]) for acorns offered during coastal and mountain feeding preference trials at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019.

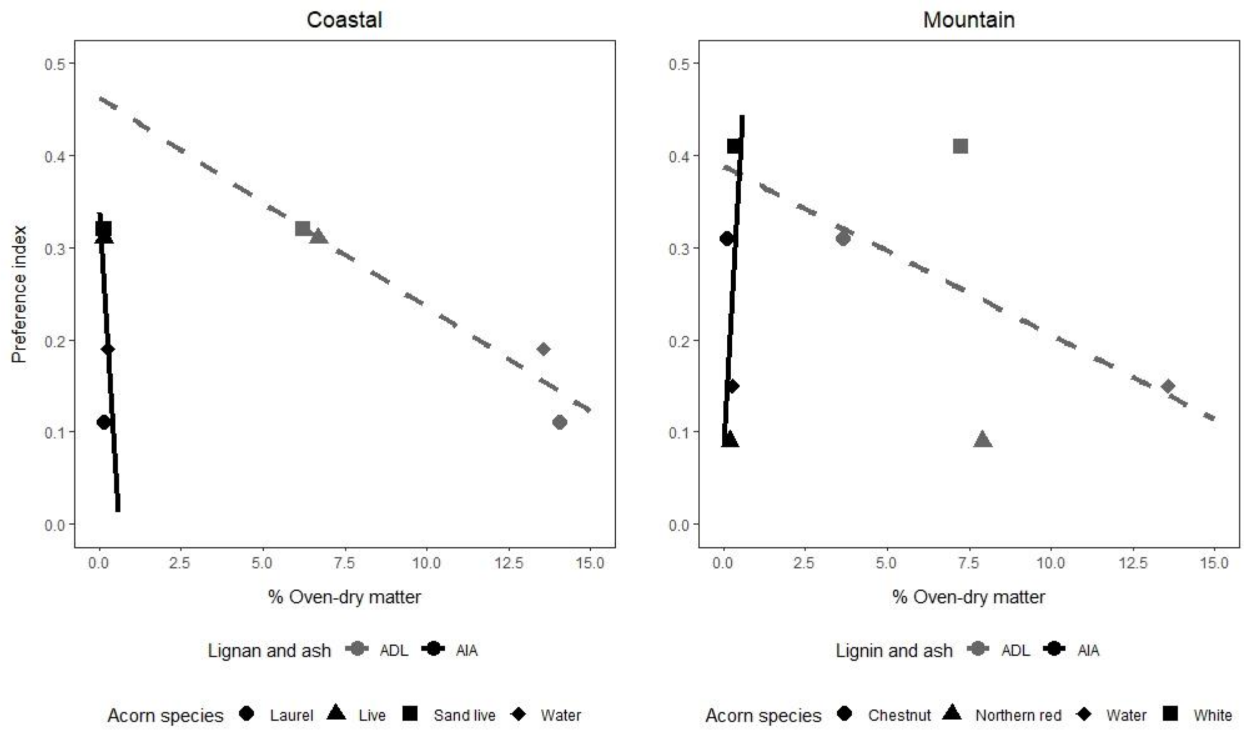

Figure 3.5. Mean preference indices (i.e., ranging from 0 = avoided to 1 = preferred) of adult female white-tailed deer in relation to acid detergent lignin (ADL; coastal [$r_s = -0.60$, $P < 0.001$], mountain [$r_s = -0.57$, $P < 0.001$]) and acid insoluble ash (AIA; coastal [$r_s = -0.30$, $P < 0.10$], mountain [$r_s = 0.22$, $P < 0.23$]) for acorns offered during coastal and mountain feeding preference trials at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019.

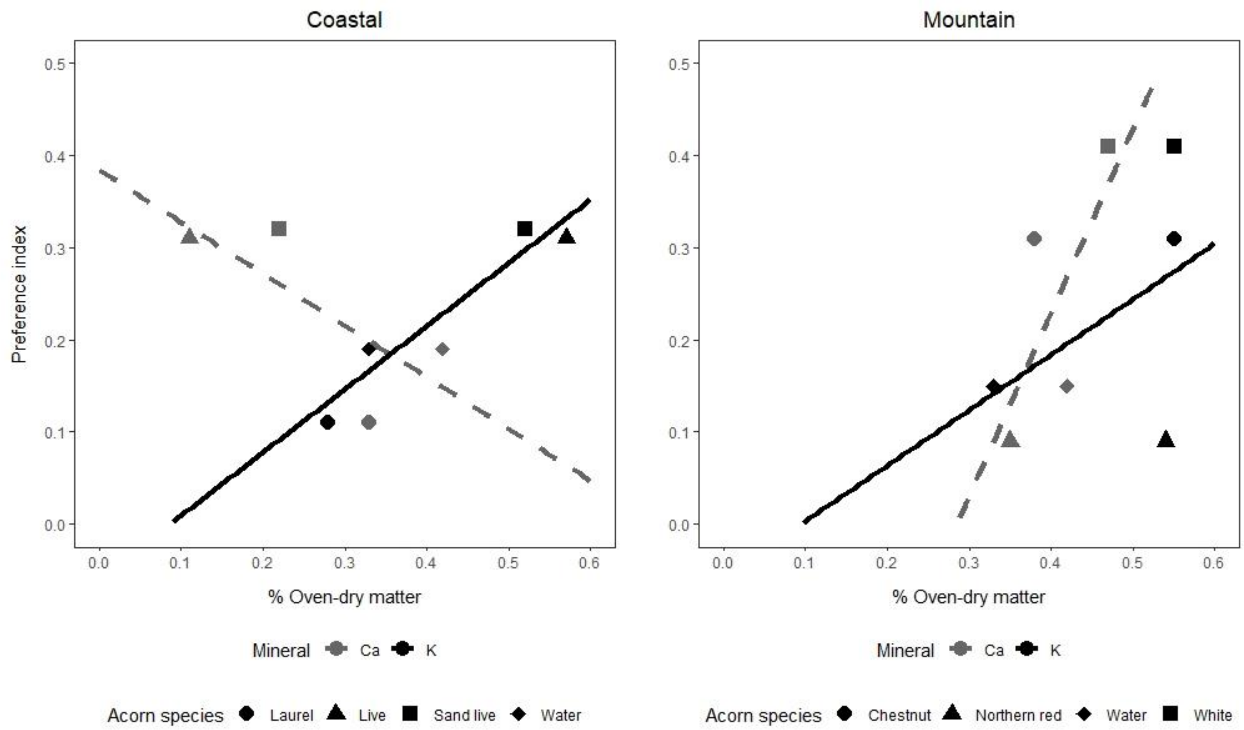

Figure 3.6. Mean preference indices (i.e., ranging from 0 = avoided to 1 = preferred) of adult female white-tailed deer in relation to calcium (Ca; coastal [$r_s = -0.43$, $P < 0.001$], mountain [$r_s = 0.55$, $P < 0.001$]) and potassium (K; coastal [$r_s = 0.58$, $P < 0.001$], mountain [$r_s = 0.57$, $P < 0.001$]) for acorns offered during coastal and mountain feeding preference trials at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019.

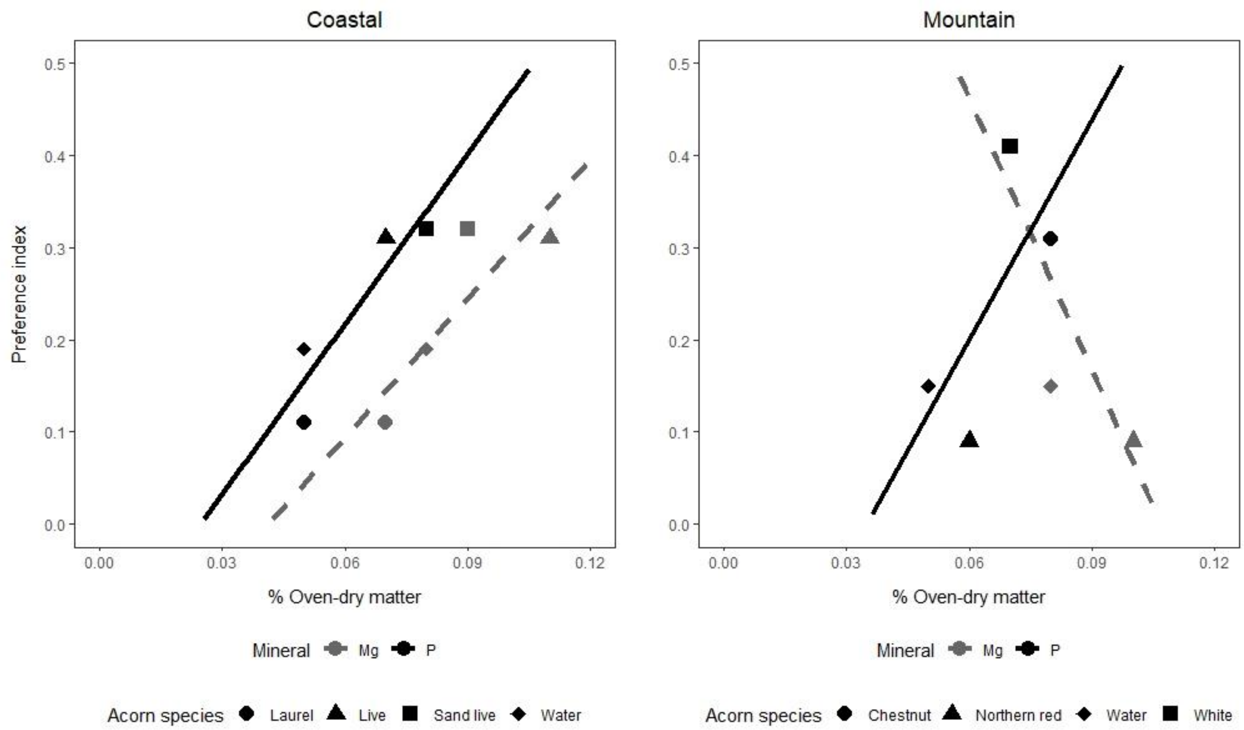

Figure 3.7. Mean preference indices (i.e., ranging from 0 = avoided to 1 = preferred) of adult female white-tailed deer in relation to magnesium (Mg; coastal [$r_s = 0.58$, $P < 0.001$], mountain [$r_s = -0.55$, $P < 0.001$]) and phosphorus (P; coastal [$r_s = 0.55$, $P < 0.001$], mountain [$r_s = 0.57$, $P < 0.001$]) for acorns offered during coastal and mountain feeding preference trials at Whitehall Deer Research Facility in Athens, GA, USA, during 2018–2019.

CHAPTER 4

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

CONCLUSIONS

The results from these studies suggest the following conclusions:

Chapter 2 – Evaluation of Expandable GPS Collars for White-tailed Deer Fawns

1) Vectronic (v1.0 and v2.0) collars performed functionally better than Telonics (v1.0 and v2.0) collars, with Vectronic collars causing less neck hair loss, exhibiting a more gradual elastic expansion, and retaining on fawns a mean (±SD) of 181 (±85) days longer than Telonics collars.
2) Young fawns with GPS collars (i.e., Telonics or Vectronic) may be less likely to detect potential dangers (e.g., predators) because uncollared fawns were more vigilant, able to keep their head upright, and unencumbered by a large, ill-fitting collar.
3) I would not recommend the use of the expandable GPS collar designs tested in this study for use on wild white-tailed deer fawns; however, researchers may have access to viable GPS fawn collars with incorporation of additional design modifications and further testing in controlled settings.
4) I recommend design modifications to GPS fawn collars including improved stitching patterns and threads, smaller batter housings, improved weight distribution, and smaller band circumferences.

5) I encourage improved communication among researchers, and between researchers and telemetry technology companies to refine development of future GPS collar designs.

6) I propose implementation of more iterative processes (e.g., Phase I, Phase II, etc.) in future collar studies to meet all appropriate, pre-determined standards before deployment in field studies.

7) I suggest future testing of traditional VHF collars alongside GPS collars to evaluate potential functional and behavioral impacts resembling observations in this study.

Chapter 3 – Preferences of Captive White-tailed Deer for Acorn Species of the Southeastern U.S.

1) Deer most preferred acorns from the two live oak species (i.e., live and sand live oak) over laurel and water oak acorns during coastal group trials, suggesting that if each of these acorn species are temporally available for forage in coastal environments, deer may more readily select live oak acorns (i.e., white oak group acorns) over red oak acorn species.

2) Deer most preferred acorns of the white oak group (i.e., white and chestnut oak) compared to acorns of the red oak group (i.e., northern red and water oak) during mountain group trials, which was expected based on the available literature surrounding preferential consumption of oak acorns by deer.

3) Deer preferred acorns reported in prior studies to be lower in tannins (i.e., white oaks), as these acorns were likely more palatable and easier on digestion compared to acorns reported to be higher in tannins (i.e., red oaks).

4) Deer during coastal group trials generally preferred acorns lower in gross energy, crude fat, NDF, ADF, ADL, and calcium, and acorns higher in crude protein, potassium, magnesium, and phosphorus.

5) Deer during mountain group trials generally preferred acorns lower in gross energy, crude fat, NDF, ADF, ADL, and magnesium, and acorns higher in crude protein, calcium, potassium, and phosphorus.

6) I recommend future studies conduct feeding trials across a greater period of time (e.g., starting in the fall and continuing into spring) and conduct nutritional analysis at multiple intervals across that time period to model preference indices in relation to acorn species and nutritional components over time and help develop a more comprehensive understanding of seasonal acorn selection by deer.

7) Further research is warranted to evaluate preferential consumption by wild deer for oak acorns found in the southeastern United States.

MANAGEMENT IMPLICATIONS

Chapter 2 – Evaluation of Expandable GPS Collars for White-tailed Deer Fawns

1) Integrating GPS technology with expandable collar designs would provide researchers with more accurate estimates of fawn survival, recruitment, movements, and habitat use to help improve management of white-tailed deer populations.

2) Considering the issues with collar size, weight, band integrity, animal welfare, and behavioral impacts, we believe that further testing of GPS collar designs for fawns in controlled settings is warranted before extensive deployment in field studies.

3) Implementation of recommendations proposed in this study will benefit future studies testing collar designs and may improve processes associated with collar development by researchers and telemetry technology companies.

Chapter 3 – Preferences of Captive White-tailed Deer for Acorn Species of the Southeastern U.S.

1) Results of this study may help managers identify differences in selective consumption of acorns by deer and provide baseline information for future research investigating oak regeneration, deer diet selection, chemical composition of foods, and deer movement ecology, behavior, and habitat use in the southeast United States
2) Considering differences in acorn preference by deer when prescribing forest-management practices (e.g., stand regeneration, thinning, chemical application, and timber harvesting) may be important to managers.
3) Managers should continue to promote diversity of species to help buffer boom-or-bust mast production patterns among oaks.