

# Influence of weather on gobbling activity of male wild turkeys

Patrick Wightman<sup>1</sup>, James Martin<sup>1</sup>, John C. Kilgo<sup>2</sup>, Emily Rushton<sup>3</sup>, Bret Collier<sup>4</sup>, and Michael Chamberlain<sup>1</sup>

<sup>1</sup>University of Georgia

<sup>2</sup>USDA Forest Service Southern Research Station

<sup>3</sup>Georgia Department of Natural Resources

<sup>4</sup>Louisiana State University

March 31, 2022

## Abstract

Gobbling activity of Eastern wild turkeys (*Meleagris gallopavo silvestris*; hereafter, turkeys) has been widely studied, focusing on drivers of daily variation. Weather variables are widely believed to influence gobbling activity, but results across studies are contradictory and often equivocal, leading to uncertainty in the relative contribution of weather variables to daily fluctuations in gobbling activity. Previous works relied on road-based auditory surveys to collect gobbling data which limits data consistency, duration, and quantity due to logistical difficulties associated with human observers and restricted sampling frames. Development of new methods using autonomous recording units (ARUs) allows researchers to collect continuous data in more locations for longer periods of time, providing the opportunity to delve into factors influencing daily gobbling activity. We used ARUs from 1 March to 31 May to detail gobbling activity across multiple study sites in the southeastern United States during 2014 – 2018. We used state-space modeling to investigate the effects of weather variables on daily gobbling activity. Our findings suggest rainfall, greater wind speeds, and greater temperatures negatively affected gobbling activity, whereas increasing barometric pressure positively affected gobbling activity. Therefore, when using daily gobbling activity to make inferences relative to gobbling chronology, reproductive phenology, and hunting season frameworks stakeholders should recognize and consider the potential influences of extended periods of inclement weather.

05 March 2021

Patrick Wightman

University of Georgia

Warnell School of Forestry and Natural Resources

Athens, GA 30602

(607) 661-3674

Pw78598@uga.edu

## Influence of weather on gobbling activity of male wild turkeys

PATRICK H. WIGHTMAN,<sup>1</sup> Email: [pw78598@uga.edu](mailto:pw78598@uga.edu) Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA

JAMES A. MARTIN, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA

JOHN C. KILGO, *USDA Forest Service, Southern Research Station, P.O. Box 700, New Ellenton, SC 29809, USA*

EMILY RUSHTON, *Georgia Department of Natural Resources – Wildlife Resources Division, Social Circle, GA 30025, USA*

BRET A. COLLIER, *School of Renewable Natural Resources, Louisiana State University Agricultural Center, Baton Rouge, LA 70803, USA*

MICHAEL J. CHAMBERLAIN, *Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, USA*

**Abstract** Gobbling activity of Eastern wild turkeys (*Meleagris gallopavo silvestris* ; hereafter, turkeys) has been widely studied, focusing on drivers of daily variation. Weather variables are widely believed to influence gobbling activity, but results across studies are contradictory and often equivocal, leading to uncertainty in the relative contribution of weather variables to daily fluctuations in gobbling activity. Previous works relied on road-based auditory surveys to collect gobbling data which limits data consistency, duration, and quantity due to logistical difficulties associated with human observers and restricted sampling frames. Development of new methods using autonomous recording units (ARUs) allows researchers to collect continuous data in more locations for longer periods of time, providing the opportunity to delve into factors influencing daily gobbling activity. We used ARUs from 1 March to 31 May to detail gobbling activity across multiple study sites in the southeastern United States during 2014 – 2018. We used state-space modeling to investigate the effects of weather variables on daily gobbling activity. Our findings suggest rainfall, greater wind speeds, and greater temperatures negatively affected gobbling activity, whereas increasing barometric pressure positively affected gobbling activity. Therefore, when using daily gobbling activity to make inferences relative to gobbling chronology, reproductive phenology, and hunting season frameworks stakeholders should recognize and consider the potential influences of extended periods of inclement weather.

**Key words** acoustic monitoring, gobbling, *Meleagris gallopavo*, Convolutional Neural Network, weather, wild turkey.

Male birds often rely on visual and auditory courtship behaviors to portray reproductive fitness to females, attract mates, and maintain social and dominance hierarchies (Williams 1984, Omland 1996, Buchholz 1997, Mateos 1999, Cornec et al. 2017). Frequency of courtship behaviors, such as vocalizations by males, change in response to conspecifics along with anthropogenic and environmental influences (Staicer et al. 1996, Berg et al. 2005, Slabbekoorn and Ripmeester 2008). Ecological theories such as the adaptive acoustic hypothesis and risk reward theory suggest birds adopt different vocalization strategies depending on environmental conditions to maximize the effectiveness and costs associated with calling (Orians 1969, Zanette et al. 2006, Lima 2009, Luther 2009).

The wild turkey (*Meleagris gallopavo* ) is a non-migratory upland game bird indigenous to North America whose mating strategy is a form of polygamy similar to exploded lekking (Krakauer 2008). Turkeys use a polygynous-promiscuous mating system, where females choose males who are competing for mating opportunities via visual displaying (e.g., strutting) and auditory vocalizations (e.g., gobbling, drumming; Healy 1992). Turkeys gobble to secure mates by attracting females, maintain territories, and compete with other males (Bailey and Rinnel 1967, Bevill 1973, Healy 1992). Gobbling activity is believed to be influenced by a variety of factors, such as time of day, timing of female reproductive activities, conspecifics, hunting, weather, predation risk, age structure, and testosterone levels (Kienzler et al. 1996, Miller et al. 1997, Chamberlain et al. 2018, Wightman et al. 2019, Wakefield et al. 2020). Wildlife managers and agencies are interested in understanding factors influencing gobbling activity, as it is the primary determinant of hunter satisfaction and is likely linked to reproductive success (Casalena 2011, Schroeder 2014, Isabelle 2015, Chamberlain et al. 2020).

Historical research relied on roadside surveys to describe gobbling activity, but results from previous studies contained notable discrepancies in regards to drivers of variation in gobbling activity. For example, early

studies reported both positive and negative effects of nesting phenology, weather, and hunting pressure on gobbling activity (Bevill 1975, Kienzler et al. 1996, Miller et al. 1997, Lehman et al. 2005, Palumbo et al. 2019). However, no definitive relationship between any of the aforementioned variables and gobbling activity was established, likely due to a lack of uniformity in data collection, coupled with logistical difficulties in obtaining high quality, detailed, spatially-explicit gobbling data. Furthermore, roadside surveys were generally not conducted during inclement weather, and can be additionally biased by observer error, sample design, and manpower limitations (Miller et al. 1997, Lehman et al. 2005, Palumbo et al. 2019).

Development and use of autonomous recording units (ARU; Rempel et al. 2005, Mennill et al. 2012, Colbert et al. 2015) offer researchers the ability to thoroughly detail gobbling activity. With advancement of ARU technology, recent studies have elucidated how factors such as time of day, nesting phenology/female receptivity and hunting influence gobbling activity using spatially and temporally robust datasets (Chamberlain et al. 2018, Wightman et al. 2019, Wakefield et al. 2020). In general, gobbling activity was highest 30 minutes prior to sunrise until 150 minutes post sunrise (hereafter; daily gobbling activity) and fluctuated considerably from one morning to the next (Wightman et al. 2019). Additional work has indicated that female nesting phenology was positively related to gobbling activity, with onset of reproductive activities resulting in an initial peak of gobbling (Chamberlain et al. 2018, Wakefield et al. 2020). Furthermore, contemporary literature has noted hunting activity may have a greater negative influence on gobbling activity than the positive effect of nesting phenology (Wightman et al. 2019, Wakefield et al. 2020). However, there is no existing literature using ARUs to investigate the relative influences of weather variation on gobbling activity. Thus, research is needed to evaluate how weather may influence gobbling activity. We hypothesized that morning weather conditions would influence gobbling activity; therefore, our objectives were to evaluate potential relationships between gobbling activity of male Eastern wild turkeys (*Meleagris gallopavo silvestris*) and a suite of weather variables across multiple study sites in the southeastern United States.

## Methods

### Study area

We conducted research on 5 study sites in Georgia and South Carolina, USA (Fig. 1). The first site, located in Aiken County, South Carolina, was the 4,400-ha Crackerneck Wildlife Management Area (CWMA), owned by the United States Department of Energy and managed by SCDNR. Landcover types on CWMA consisted of upland and bottomland hardwoods, mixed pine-hardwoods, planted pine stands, and wildlife openings. Turkey hunting season opened annually on 1 April with a youth hunt on the Saturday prior, and closed 1 May, with hunting occurring only on Fridays and Saturdays. The second site in South Carolina was the United States Department of Energy's Savannah River Site (SRS), which consisted of 78,000 ha located in Aiken and Barnwell counties. The SRS was mostly forested and consisted of upland and bottomland hardwoods, mixed-pine hardwoods, and planted stands of longleaf and loblolly pine. Since 1951, turkey hunting pressure on SRS was limited. Hunting was restricted to an annual 2-day hunt during the third weekend of April for mobility-impaired hunters that began in 2002. We collected data on CWMA and SRS during 2014-2018. For more detailed descriptions of site-specific conditions on the South Carolina study sites, see Wightman et al. (2019).

From 2015 to 2018, we collected data on 3 contiguous Wildlife Management Areas (WMAs) known as the Webb WMA Complex in Hampton and Jasper counties in South Carolina. The Webb WMA Complex was 10,483-ha dominated by pine (*Pinus* spp.) forests consisting mostly of loblolly pine (*P. taeda*) and longleaf pine (*P. palustris*), with hardwood stands adjacent to riparian drainages, and bottomland hardwoods and wetlands along the Savannah River. The Webb WMA Complex was actively managed for a variety of wildlife by the South Carolina Department of Natural Resources. Hunting season for male turkey opened annually on 1 April with a youth hunt on the Saturday prior and ended in the first week of May, and hunting was permitted Monday-Saturdays.

During 2017-2018, we collected data on two WMAs in the Piedmont region of Georgia, USA. Cedar Creek WMA (CCWMA) was a 16,187-ha area located in Jasper, Jones, and Putnam counties owned by the United

States Department of Agriculture Forest Service (USFS) and managed in partnership with the Georgia Department of Natural Resources-Wildlife Resources Division (GADNR). Cedar Creek WMA consisted of upland loblolly pine stands, with interspersed areas of mixed pine-hardwood forests, and expanses of hardwood dominated forests. In 2017, a turkey hunting season was open to the public from 25 March to 15 May, whereas in 2018 it spanned from 24 March - 15 May. We also collected data on the 4,613-ha B. F. Grant WMA (BFG) located in Putnam County, Georgia. The BFG was owned by the Warnell School of Forestry and Natural Resources at the University of Georgia and managed in partnership with the GADNR. The area consisted mostly of planted loblolly pine forests, hardwood forests, and agricultural fields used for cattle grazing and hay production. Turkey hunting season on BFG was split into three parts, the first a youth only hunt which occurred from 25 March - 2 April in 2017 and 24 March - 1 April in 2018. The second hunt was an 80-person quota from 3 April - 9 April in 2017 and 2 April - 8 April in 2018. The final hunt was open to the general public and occurred 10 April - 15 May in 2017 and 2 April - 15 May in 2018. For details on site-specific conditions on BFG and CCWMA see Wakefield et al. (2020).

## Data collection and manipulation

We deployed ARUs (Song Meter Model SM2 and SM4, Wildlife Acoustics, Concord, MA, USA) to collect ambient sound from 1 March – 31 May. We deployed 15 ARUs on the Webb WMA Complex during 2015 – 2018, 10 on CWMA during 2014 – 2018, 20 on SRS during 2014 – 2018, 16 on CCWMA in 2017, and 8 on BFG in 2017. We increased sampling efforts during 2018 in Georgia by deploying 20 additional ARUs on CCWMA and 10 on BFG. We placed ARUs >2 km apart to prevent multiple units from detecting the same call (Wightman et al. 2019, Wakefield et al. 2020). We attached ARUs to tree trunks approximately 3m off the ground and placed an external microphone between 6m and 10m above the ground on the same tree (Wightman et al. 2019). We placed ARUs at locations observed to have turkey activity based on field observations and global positioning system (GPS) locations of wild turkeys collected during previous research (Wightman et al. 2019). We used ambient sound recorded from 30 minutes prior to sunrise until 150 minutes post sunrise as this is when > 75% of vocalizations occurred (Wightman et al. 2019, Wakefield et al. 2020).

We used a Convolutional Neural Network (CNN) developed to autonomously search for turkey gobbles (Wightman et al. 2021). We implemented the CNN in Python (Python Software Foundation, Wilmington, DE, USA) with the Keras library (Chollet 2015) using a backend of the open-source TensorFlow software developed by Google (Abadi et al. 2015). For each potential gobbler selected by the CNN, a record was created containing call location in the spectrogram, date and time stamp, and a 3 second sound file of the potential gobbler. We auditorily verified all selections and classified each as a true or false gobbler, producing daily counts of gobblers on all sites.

We collected weather data for SRS and CWMA from 2 weather stations located on SRS maintained by the U.S. Department of Energy and U.S. Department of Agriculture Forest Service. We used the most centrally located weather station on SRS to describe weather metrics associated with gobbling activity onsite. The second weather station was on the southern border of SRS, approximately 10.5 km from the center of CWMA, and was used for gobbling evaluation on CWMA. For the Webb WMA Complex, CCWMA, and BFG, we collected weather metrics from the closest National Oceanic and Atmospheric Administration (NOAA) weather station. The closest weather station to the Webb WMA Complex was located in Varnville, SC (35 km), whereas the closest station to CCWMA (25 km) and BFG (35 km) was near Eatonton, GA. Although previous authors have suggested the potential for placing weather stations at each ARU (Palumbo et al. 2019, Wightman et al. 2019) such a study design was not logistically feasible. We offer that using weather data collected on the same study site or within the distances detailed above is sufficient for detailing how daily changes in local weather conditions influence gobbling activity. We calculated mean daily values from 15-minute weather recordings from 30 minutes prior to 150 minutes after sunrise for temperature (C°), relative humidity percentage, and wind speed (kph). For barometric pressure (mb) we calculated the mean for each morning and then subtracted it from the prior morning to get a change in barometric pressure. For precipitation, we classified whether rain occurred (Yes = 1, No = 0) from 30 minutes before to 150 minutes

after sunrise.

## Data analysis

Our final dataset included time series data for all weather variables (scaled by subtracting variable means from observed values and dividing by the standard deviation) and daily gobbling counts. With the spatially and temporally coupled data, we used state space modeling to evaluate the effects of weather variables on daily gobbling activity. The state space model accounted for correlated observations and included observation error while modeling the influences of weather variables on gobbling activity. We used a hierarchical state space model that allowed us to decompose temporally correlated weather data and gobbling counts into a process variation and observation error (Kery and Schaub 2012). With the weather variables being the parameters of interest, the state space model allowed us to investigate the process variation in gobbling counts relative to stochasticity in the weather variables. We calculated Pearson’s correlation coefficients to test for collinearity between each of our covariates and excluded covariates with a  $r > 0.60$ . We fit the state space model within the jagsUI package (Kellner 2018) in program R (R Core team 2020) to estimate the effects of weather on daily gobbling activity.

We fit the Bayesian state space model to counts of daily gobbles (N) at each site (K) during each year (i). We treated daily gobbling counts like counts in a population model but we modeled the abundance of gobbles instead of animals. The process model was:

$$r_{\text{expected}(t)} = X_{\log(N[t-1],k,i)} + \text{Site}_{(k)} + \beta_{\text{temperature}} * X_{\text{temperature}(t,k,i)} + \beta_{\text{wind}} * X_{\text{wind}(t,k,i)} + \beta_{\text{bp}} * (X_{\text{bp}(t,k,i)} - X_{\text{bp}(t-1,k,i)}) + \beta_{\text{humidity}} * X_{\text{humidity}(t,k,i)} + \beta_{\text{precipitation}} * X_{\text{precipitation}(t,k,i)} + \text{Year} + \log(\text{Units})$$

$$r_t \sim \text{Normal}(r_{\text{expected}[t]}, \tau_{\text{process}})$$

$$\text{Log}(N_{t+1}) = \text{log}(N_t) +$$

$$r_t$$

Where  $r_{\text{expected}(t)}$  was the expected change in daily gobbling activity, Site was the fixed effect for each of the 5 sites,  $\beta_{\text{temperature}}$  was the coefficient for the effect of temperature in matrix  $X_{\text{temperature}}$ ,  $\beta_{\text{wind}}$  was the coefficient for the effect of wind in matrix  $X_{\text{wind}}$ ,  $\beta_{\text{bp}}$  was the coefficient for the effect of the change in barometric pressure in matrix  $X_{\text{bp}}$ ,  $\beta_{\text{humidity}}$  was the coefficient for the effect of humidity in matrix  $X_{\text{humidity}}$ ,  $\beta_{\text{precipitation}}$  was the coefficient for the effect of precipitation in matrix  $X_{\text{precipitation}}$ , Year was modelled as a random effect, and Units was an offset term used to account for the number of ARUs recording. We modeled the observation process as follows:  $y_{t,k,i} \sim \text{Poisson}(\log(N_t))$  where  $y_{t,k,i}$  was the logged observed number of gobbles each day(t) at each site during each year. We calculated 95% credible intervals for each parameter estimate of interest. For the random effect of year and to account for process variation, we used a gamma distribution for the priors with a precision of 0.001. For the rest of the parameters, we used a normal distribution with a mean of 0 and a precision of 0.001. We used Markov chain Monte Carlo (MCMC) to estimate the posterior distributions of the model parameters. We generated 3 MCMC chains using a thinning rate of 10,000 iterations per chain and 2,500 burn in values. To check for convergence, we investigated trace plots of the MCMC chains and used Gelman-Rubin statistic to calculate R-values, with R-values less than 1.1 indicating model convergence (Gelman et al. 2004).

## Results

We autonomously searched 75,858 hours of ambient sound for potential gobbles. The CNN identified 324,236 potential gobbles of which 194,655 (60%) were true gobbles (Table 1). Mean gobbles per ARU from 1 March - 31 May was highest on SRS ( $937 \pm 326$ , mean  $\pm$  SD), 11% less on CWMA ( $838 \pm 404$ ), 52% less on the Webb WMA complex ( $443 \pm 120$ ), 46% less on BFG ( $507 \pm 38$ ), and 61% less on CCWMA ( $369 \pm 130$ , Table 1).

The state-space model accurately predicted gobbling activity compared to our observed gobbling activity (Figure 2) and R-values indicated model convergence (Table 2). Results from the state space model indicated the occurrence of rain most impacted (negatively) gobbling activity (Table 2). Where the mean expected

number of daily gobbles would be 21 ( $CrI = 15, 30$ ) without rain, compared to 12 ( $CrI = 7, 22$ ) if rain occurred. Conversely, an increase of barometric pressure from one day to the next was positively associated with gobbling activity (Figure 3, Table 2). We found gobbling activity was negatively influenced by increased temperatures (Figure 4, Table 2), and by greater wind speed with the largest effect occurring when wind speeds exceeded 10 kilometers per hour (Figure 5, Table 2). Humidity had no effect on the average predicted rate of change in gobbles across all study sites and years (Table 2).

## Discussion

Previous literature detailing how weather influences gobbling activity has reported contradictory results (Scott and Boeker 1972, Bevill 1973, Kienzler et al. 1996, Miller 1997, Palumbo et al. 2019), leading to uncertainty in the relative contribution of weather variables to daily fluctuations in gobbling activity. We used the most comprehensive dataset currently available on wild turkey gobbling activity, coupled with local weather metrics, to evaluate relationships between gobbling activity and weather. Collectively, our findings suggest weather variables can influence daily gobbling activity and are at least partially responsible for oscillations in gobbling activity throughout the spring reproductive season.

Gobbling is a behavior males use to attract females and ensure reproductive opportunities (Buchholz 1997). However, gobbling increases predation risk as predators are attracted to calls, so males must balance increasing predation risk with attracting mates (Tuttle and Ryan 1981, Burk 1982, Jennions et al. 1997). In birds, weather conditions can also increase predation risk, therefore males may adopt varying calling strategies in response to weather conditions (Carr and Lima 2010, Digby et al. 2014). We found rain had the greatest influence on gobbling activity, as has been shown in earlier works (Bevil 1973, Kienzler et al. 1996). During rain events, calling males may be more vulnerable to predation as their hearing and vision, which they rely on for detecting predators, are compromised (Healy 1992, Candolin and Voigt 1998, Hedrick 2000). Furthermore, during rain events sound attenuation is increased, making it harder for the gobble to be heard by other individuals (Lengagne and Slater 2002). Alternatively, rain may simply reduce the ability of the ARU to detect gobbles, although we detected 21,180 gobbles during rain events and literature on other bird species reported that rain negatively influenced calling (Staicer et al. 1996, Bruni et al. 2014, Digby et al. 2014). We posit that the influence of rain on gobbling activity recorded by ARUs is likely a combination of detection and ecology, but when reporting gobbling chronology should be considered.

Increases in animal activity and calling have previously been associated with increases in barometric pressure across multiple species (Oseen and Wassersug 2002, Wellendorf et al. 2004, Pellegrino et al. 2013, Zagvazdina et al. 2015). Changing barometric pressure is a well-known predictor of storm fronts, with barometric pressure falling as inclement weather approaches and rising as the storm system dissipates (Saucier 2003, Breuner et al. 2013). Miller et al. (1997) found no relationship between gobbling and barometric pressure, but we observed an increase in barometric pressure from one day to the next resulted in increased gobbling activity. Given changes in barometric pressure and its relationship to inclement weather such as rain, we conclude that this relationship is best explained by turkeys gobbling more in weather conditions not associated with storm systems.

Extant literature has noted a significant relationship between decreased calling and higher temperature in various birds that use auditory courtship behaviors (Hansen and Guthery 2001, Gudka et al. 2019). Vocalization and thermal relationships are likely related to overheating and higher metabolic rates that can occur with increased ambient temperatures, especially for endotherms who use energetically costly courtship behaviors (Dillon et al. 2010, Silva et al. 2015). We observed a similar relationship between higher temperatures and gobbling activity but note that previous studies at southern latitudes reported no relationship between temperature and gobbling activity (Miller et al. 1997, Palumbo et al. 2019), whereas at more northern latitudes studies have reported positive relationships between gobbling and temperature (Kienzler et al. 1996). One could speculate that this relationship could be related to the removal of males causing drops in gobbling later in the sampling period when temperatures are warmer. However, given that we had 5 years of data on an un-hunted site where gobbling continued until the end of the sampling period (Figure 2), we suspect that this is not the case. Wild turkeys at southern latitudes may reduce gobbling at higher temperatures, but we

offer that the pattern may not be similar at northern latitudes.

Sound attenuation increases at greater wind speeds, and previous studies have demonstrated wind can negatively influence calling frequency and the ability to hear calls in multiple species (Lengagne 1999, Lengagne and Slater 2002, Yip et al. 2017). We observed that greater wind speeds had a negative effect on daily gobbling, consistent with previous studies (Bevill 1973, Kienzler et al. 1996, Miller et al. 1997). The ability for either human observers or ARUs to detect gobbling as wind speeds increase may be diminished (Kienzler et al. 1996). Alternatively, during high wind speeds birds may change behaviors as perceived risk increases, as individuals have increased difficulty detecting predators due to confusion with moving vegetation (Boyko et al. 2004, Carr and Lima 2010). We suspect males may be less inclined to gobble as wind speeds increase because the desired outcome from calling may be limited by the ability of receptive females to hear the call, and because predation risk may increase.

Wakefield et al. (2020) used the same modeling approach that we used, focused on describing the influences of female reproduction (laying or incubating) and cumulative removal of males on daily gobbling activity. Wakefield et al. (2020) found the proportion of females in reproduction positively influenced gobbling activity, but the impact of male removal at the same time had a greater negative impact on gobbling activity. We also recognize other variables not measured in our or previous studies may be contributing to variation in daily gobbling, such as varying levels of testosterone in males, interactions/encounters with females, and population vital rates such as male age structure (Miller et al. 1997, Chamberlain et al. 2018, Wakefield et al. 2020).

As gobbling activity is positively correlated with hunter satisfaction and linked to reproduction, it is often a key determinant used by state agencies when considering regulatory frameworks (Bevill 1975, Hoffman 1990, Little et al. 2001, Casalena et al. 2011, Isabelle et al. 2015). Given our results, we suggest that when describing gobbling activity, managers should account for how weather patterns may influence gobbling chronology. Weather variables should be coupled with site specific reproductive timing and harvest data to fully understand gobbling chronology on a given site. We recommend future studies investigate the relationship between daily gobbling activity, weather, and reproductive phenology of females in an un-hunted population and populations subjected to varying hunting seasons and harvest rates.

## Declarations

We gratefully acknowledge the numerous technicians, undergraduate students, and graduate students at Louisiana State University and the University of Georgia for their efforts collecting data and verifying gobblers. M. A. Vukovich, USDA Forest Service, was especially instrumental in fieldwork and data management. Funding and support were provided by the Georgia Department of Natural Resources, South Carolina Department of Natural Resources, the Louisiana State University Agricultural Center, the United States Department of Energy – Savannah River, the USDA Forest Service – Savannah River, the USDA Forest Service Southern Research Station, and the Warnell School of Forestry and Natural Resources at the University of Georgia. This manuscript is partially based on work supported by the National Institute of Food and Agriculture, United States Department of Agriculture, McIntire-Stennis project number 1005302.

## Data availability statement

All raw gobbling and weather data from this study will be made openly available in Dryad if the article is accepted for publication.

## References

- Abadi, M., A. Agarwal, P. Barham, E. Brevdo, Z. Chen, C. Citro, G. S. Corrado, A. Davis, J. Dean, M. Devin, S. Ghemawat, I. J. Goodfellow, A. Harp, G. Irving, M. Isard, Y. Jia, R. Józefowicz, L. Kaiser, M. Kudlur, J. Levenberg, D. Mane, R. Monga, S. Moore, D. G. Murray, C. Olah, M. Schuster, J. Shlens, B. Steiner, I. Sutskever, K. Talwar, P. A. Tucker, V. Vanhoucke, V. Vasudevan, F. B. Viégas, O. Vinyals, P. Warden, M. Wattenberg, M. Wicke, Y. Yu, and X. Zheng. 2015. Tensorflow: large-scale machine learning on heterogeneous systems. arXiv:1603.04467

- Bailey, R. W., and K. T. Rinnell. 1967. Events in the turkey year. Pages 73–91 in O. H. Hemitt, editor. The wild turkey and its management. The Wildlife Society, Washington, D.C., USA.
- Berg, M. L., N. H. Beintema, J. A. Welbergen, and J. Komdeur. 2005. Singing as a handicap: the effects of food availability and weather on song output in the Australian reed warbler *Acrocephalus australis*. *Journal of Avian Biology* 36:102–109.
- Bevill, W. V., Jr. 1973. Some factors influencing gobbling activity among turkeys. *Proceedings of the Southeastern Association of Game and Fish Commissioners* 27:62–73.
- Bevill, W. V., Jr. 1975. Setting spring gobbler hunting seasons by timing peak gobbling. *Proceedings of the National Wild Turkey Symposium* 3:198–204.
- Boyko, A. R., R. M. Gibson, J. R. Lucas. 2004. How predation risk affects the temporal dynamics of avian leks: greater sage grouse versus golden eagles. *The American Naturalist* 163:154–165.
- Breuner, C. W., R. S. Sprague, S. H. Patterson, H. A. Woods. 2013. Environment, behavior, and physiology: do birds use barometric pressure to predict storms? *The Journal of Experimental Biology* 216:1982–1990.
- Bruni, A., D. J. Mennill, J. R. Foote. 2014. Dawn chorus start time variation in a temperate bird community: relationships with seasonality, weather, and ambient light. *Journal of Ornithology* 155:877–890.
- Buchholz, R. 1997. Male dominance and variation in fleshy head ornamentation in wild turkeys. *Journal of Avian Biology* 28:223–230.
- Burk, T. 1982. Evolutionary significance of predation on sexually signaling males. *Florida Entomologist* 65:90–104.
- Candolin, U., and H. R. Voigt. 1998. Predator-induced nest site preference: safe nests allow courtship in sticklebacks. *Animal Behaviour* 56:1205–1211.
- Carr, J. M. and S. L. Lima. 2010. High wind speeds decrease the responsiveness of birds to potentially threatening moving stimuli. *Animal Behaviour* 80:215–220.
- Casalena, M. J., C. S. Rosenberry, and R. C. Boyd. 2011. Knowledge, characteristics and attitudes of wild turkey hunters in Pennsylvania. *Proceedings of the National Wild Turkey Symposium* 10:41–48.
- Chamberlain, M. J., P. H. Wightman, B. S. Cohen, and B. A. Collier. 2018. Gobbling activity of Eastern wild turkeys relative to male movements and female nesting phenology in South Carolina. *Wildlife Society Bulletin* 42:632–642.
- Colbert, D. S., J. A. Ruttinger, M. Streich, M. J. Chamberlain, L. M. Conner, and R. J. Warren. 2015. Application of autonomous recording units to monitor gobbling activity by wild turkey. *Wildlife Society Bulletin* 39:757–763.
- Cornec, C., Y. Hingrat, T. Aubin, and F. Rybak. 2017. Booming far: the long-range vocal strategy of a lekking bird. *Royal Society Open Science* 4:170594.
- Digby, A., M. Towsey, B. D. Bell, P. D. Teal. 2014. Temporal and environmental influences on the vocal behavior of a nocturnal bird. *Avian Biology* 45:591–599.
- Dillon, M. E., G. Wang, R. B. Huey. 2010. Global metabolic impacts of recent climate warming. *Nature* 467:704–706.
- Gelman, A., J. B. Carlin, H. S. Stern, and D. B. Rubin. 2004. Posterior simulation. Chapman and Hall/CRC, Boca Raton, Florida, USA.
- Gudka, M., C. D. Santos, P. M. Dolman, J. M. Abad-Gomez, J. P. Silva. 2019. Feeling the heat: elevated temperature affects male display activity of a lekking grassland bird. *PLoS ONE* 14: e0221999.



- Hansen, H. M., and F. S. Guthery. 2001. Calling behavior of bobwhite males and call-count index. *Wildlife Society Bulletin* 29:145–152.
- Healy, W. M. 1992. Behavior. Pages 46-65 *in* J. G. Dickson, editor. *The wild turkey: biology and management*. Stackpole Books, Harrisburg, Pennsylvania, USA.
- Hedrick A. V. 2000. Crickets with extravagant mating songs compensate for predation risk with extra caution. *Proceedings of the Royal Society* 267:671–675.
- Hoffman, R. W. 1990. Chronology of gobbling and nesting activities of Merriam’s wild turkeys. *Proceedings of the National Wild Turkey Symposium* 6:25–31.
- Isabelle, J. L., and R. A. Reitz. 2015. Characteristics, attitudes, and preferences of spring wild turkey hunter in Missouri. *Proceedings of the National Wild Turkey Symposium* 11:249–258.
- Jennions, M. D., and M. Petrie. 1997. Variation in mate choice and mating preferences: a review of causes and consequences. *Biological Review* 72:283–327.
- Kellner, K. 2018. jagsUI: a wrapper around rjags to streamline JAGS analyses. R package version 1. <https://rdr.io/cran/jagsUI/>. Accessed 5 Aug 2018.
- Kienzler, J. M., T. W. Little, and W. A. Fuller. 1996. Effects of weather, incubation, and hunting on gobbling activity in wild turkeys. *Proceedings of the National Wild Turkey Symposium* 7:61–68.
- Krakauer, A. H. 2008. Sexual selection and the genetic mating system of wild turkeys. *Condor* 110:1–12.
- Lehman, C. P., L. D. Flake, M. A. Rumble, and D. J. Thompson. 2005. Gobbling of Merriam’s turkeys in relation to nesting and occurrence of hunting in the Black Hills, South Dakota. *Proceedings of the National Wild Turkey Symposium* 9:343–348.
- Lengagne, T., T. Aubin, J. Lauga, P. Jouventin. 1999. How do king penguins (*Aptenodytes patagonicus*) apply the mathematical theory of information to communicate in windy conditions? *Royal Society* 266:1623–1628.
- Lengagne, T., and J. B. Slater. 2002. The effects of rain on acoustic communication: Tawny owls have good reason for calling less in wet weather. *The Royal Society Proceedings of Biological Sciences* 269: 2121–2125.
- Lima, S. L. 2009. Predators and the breeding bird: behavioral and reproductive flexibility under the risk of predation. *Biological Review* 84:485–513.
- Little, D. A., J. L. Bowman, G. A. Hurst, R. S. Seiss, and D. L. Minnis. 2001. Evaluating turkey hunter attitudes on Wildlife Management Areas in Mississippi. *Proceedings of the National Wild Turkey Symposium* 8:223–231.
- Luther, D. 2009. The influence of the acoustic community on songs of birds in a neotropical rain forest. *Behavioral Ecology* 20:864–871.
- Mateos, C., J. Carranza. 1999. Effects of male dominance and courtship display on female choice in the ring-necked pheasant. *Behavioral Ecology and Sociobiology*. 45:235–244.
- Mennill, D. J., M. Battiston, D. R. Wilson, J. R. Foote, and S. M. Doucet. 2012. Field test of an affordable, portable, wireless microphone array for spatial monitoring of animal ecology and behavior. *Methods in Ecology and Evolution* 3:704–712.
- Miller, D.A., G. A. Hurst, and B. D. Leopold. 1997. Factors affecting gobbling activity on wild turkeys in central Mississippi. *Proceedings of the Annual Conference of Southeastern Association of Fish and Wildlife Agencies*. 51:352–361.
- Norman, G. W., C. I. Taylor, K. H. Pollock, D. E. Steffen, J. C. Pack, and K. Tsai. 2001. Reproductive chronology, spring hunting, and illegal kill of female wild turkeys. *Proceedings of the National Wild Turkey*

Symposium 8:269–280.

Omland, K. 1996. Female mallard mating preferences for multiple male ornaments. *Behavioral Ecology and Sociobiology* 39:353–360.

Orians, G. H. 1969. On the evolution of mating systems in birds and mammals. *American Naturalist* 103:589–603.

Oseen, K. L. and R. J. Wassersug. 2002. Environmental factors influencing calling in sympatric anurans. *Oecologia* 133:616–625.

Palumbo, M. D., F. J. Vilella, G. Wang, B. K. Strickland, D. Godwin, P. G. Dixon, B. D. Rubin, and M. A. Lashley. 2019. Latitude and daily-weather effects on gobbling activity of wild turkeys in Mississippi. *International Journal of Biometeorology* 63:1059–1067.

Pellegrino, A. C., M. F. G. V. Penaflor, C. Nardi, W. Bezner-Kerr, C. G. Guglielmo, J. M. S. Bento, J. N. McNeil. 2013. Weather forecasting by insects: modified sexual behaviour in response to atmospheric pressure changes. *PLoS ONE* 8: e75004.

R Core Team. 2020. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Rempel, R. S., K. A. Hobson, G. Holborn, S. L. Wilgenburg, and J. Elliott. 2005. Bioacoustic monitoring of forest songbirds: interpreter variability and effects of configuration and digital processing methods in the laboratory. *Journal of Field Ornithology* 76:1–11.

Saucier, W. J. 2003. Principles of meteorological analysis. New York, NY: Dover Publications.

Schaub, M. and M. Kery. 2012. Hierarchical models in population ecology. *Animal Conservation* 15: 125–126.

Schroeder, S. 2014. Minnesota spring wild turkey hunting: a study of hunters' opinions and activities. Final report submitted to Minnesota Department of Natural Resources 104pp.

Silva, J. P., I. Catry, J. M. Palmeirim, F. Moreira. 2015. Freezing heat: thermally imposed constraints on the daily activity patterns of a free-ranging grassland bird. *Ecosphere* 6:1–13.

Slabbekoorn, H. and E. A. P. Ripmeester. 2008. Birdsong and anthropogenic noise: implications and applications for conservation. *Molecular Ecology* 17:72–83.

Scott, V. E., and E. L. Boeker. 1972. An evaluation of wild turkey call counts in Arizona. *Journal of Wildlife Management* 36:628–630.

Staicer, C. A., D. A. Spector, and A.G. Horn. 1996. The dawn chorus and other diel patterns in acoustic signaling. Pages 426–453 *in* Ecology and Evolution of Acoustic Communication in Birds. Cornell University Press, Ithaca, NY.

Tuttle, M. D., and M. J. Ryan. 1981. Bat predation and the evolution of frog vocalizations in the neotropics. *Science* 214:677–678.

Wakefield, C. T., P. H. Wightman, J. A. Martin, B. S. Cohen, B. A. Collier, M. J. Chamberlain. 2020. Hunting and nesting phenology influence gobbling of Eastern wild turkeys. *Journal of Wildlife Management* 84:448–457.

Wellendorf, S.D., W.E. Palmer, P.T. Bromley. 2004. Estimating calling rates of Northern bobwhite coveys and measuring abundance. *Journal of Wildlife Management* 68:672–682.

Wightman, P. H., J. C. Kilgo, M. Vukovich, J. R. Cantrell, C. R. Ruth, B. S. Cohen, M. J. Chamberlain, and B. A. Collier. 2019. Gobbling chronology of eastern wild turkeys in South Carolina. *Journal of Wildlife Management* 83:325–333.

Wightman, P. H., D. W. Henrichs, B. A. Collier, and M. J. Chamberlain. 2022. Comparison of methods for automated identification of wild turkey gobbles. *Wildlife Society Bulletin* 1–10. <https://doi.org/10.1002/wsb.1246>

Williams, L. E. 1984. *The voice and vocabulary of the wild turkey*. Gainesville, Florida, USA.

Yip, D. A., E. M. Bayne, P. Solymos, J. Campbell, D. Proppe. 2017. Sound attenuation in forest and roadside environments: implications for avian point-count surveys. *American Ornithological Society* 119:73–84.

Zagvazdina, N. Y., T. M. Paris, B. J. Udell, M. Stanislauskas, S. Mcneill, S. A. Allan, R. W. Mankin. 2015. Effects of atmospheric pressure trends on calling, mate-seeking, and phototaxis of *Diaphorina citri*. *Entomological Society of America* 108:762–770.

Zanette, L., M. Clinchy, and J. N. M. Smith. 2006. Combined food and predator effects on songbird nest survival and annual reproductive success: results from a bi-factorial experiment. *Oecologia* 147:632–640.

Zuk, M., and G. R. Kolluru. 1998. Exploitation of sexual signals by predators and parasitoids. *Quarterly Review of Biology* 73:415–438.

Table 1. Detections, gobbles, and gobbles per autonomous recording unit (ARU) for the Webb Wildlife Management Area Complex (Webb), Savannah River Site (SRS) and Crackerneck Wildlife Management Area (CWMA) in South Carolina and Cedar Creek Wildlife Management Area (CCWMA) and B.F. Grant Wildlife Management Area (BFG) in Georgia from 2014 through 2018.

Site	Year	Detections	Gobbles	Gobbles (%)	Gobbles per ARU
SRS	2014	29,138	21,484	74	1,074.20
SRS	2015	22,409	17,242	77	862.10
SRS	2016	25,039	18,236	73	911.80
SRS	2017	35,043	27,366	78	1,368.30
SRS	2018	16,434	9,454	58	472.70
CWMA	2014	19,214	14,242	74	1,424
CWMA	2015	10,614	6,234	59	623.40
CWMA	2016	12,458	7,032	56	703.20
CWMA	2017	14,941	10,518	70	1051.80
CWMA	2018	8,246	3,892	47	389.20
Webb	2015	12,476	8,063	65	537.53
Webb	2016	12,946	8,305	64	553.67
Webb	2017	9,096	4,701	52	313.40
Webb	2018	11,793	5,524	47	368.27
BFG	2017	15,014	3,839	26	479.88
BFG	2018	26,404	7,480	29	534.29
CCWMA	2017	5,176	4,437	86	277.31
CCWMA	2018	37,795	16,606	44	461.28

Table 2. Parameters and associated means, standard deviations (sd), and credible intervals from a state-space model evaluating the relationship between daily gobbling activity by male wild turkeys and weather variables for the Webb Wildlife Management Area Complex (Webb), Savannah River Site (SRS) and Crackerneck Wildlife Management Area (CWMA) in South Carolina and Cedar Creek Wildlife Management Area (CCWMA) and B.F. Grant Wildlife Management Area (BFG) in Georgia from 2014 through 2018.

Parameters	Mean	SD	2.50%	97.50%	R-value
BFG	-0.07	0.15	-0.31	0.26	1
CCWMA	-0.01	0.15	-0.36	0.23	1

CWMA	0.20	0.115	-0.01	0.42	1
SRS	0.11	0.09	-0.04	0.29	1
Webb	0.10	0.12	-0.13	0.33	1
Temperature	-0.21	0.05	-0.30	-0.11	1
Wind	-0.16	0.05	-0.33	-0.13	1
Barometric Pressure	0.28	0.09	0.14	0.48	1
Humidity	0.09	0.06	-0.02	0.21	1
Precipitation	-0.56	0.12	-0.76	-0.29	1
2014	0.01	0.07	-0.13	0.18	1
2015	0.02	0.07	-0.11	0.19	1
2016	0.02	0.07	-0.11	0.18	1
2017	-0.01	0.07	-0.19	0.09	1
2018	-0.03	0.07	-0.20	0.09	1

Figure 1. Location of Webb Wildlife Management Area Complex, Crackerneck Wildlife Management Area, the Savannah River Site in South Carolina, USA, and B.F. Grant and Cedar Creek Wildlife Management Areas in Georgia, USA.

Figure 2. Predicted daily gobbling activity from state space model (dotted line) with 95% credible intervals (shaded grey) compared to observed daily gobbling activity (black line) on the Savana River Site in South Carolina, USA, 2014.

Figure 3. The expected number of gobbles ( $r_{\text{expected}(t)} * 20$ ) with 95% credible intervals as a function of change in barometric pressure (mb) across all 5 sites in South Carolina and Georgia, USA, 2014-2018.

Figure 4. The expected number of gobbles ( $r_{\text{expected}(t)} * 20$ ) with 95% credible intervals as a function of temperature ( $^{\circ}\text{C}$ ) across all 5 sites in South Carolina and Georgia, USA, 2014-2018.

Figure 5. The expected number of gobbles ( $r_{\text{expected}(t)} * 20$ ) with 95% credible intervals as a function of wind speed (km/hr) across all 5 sites in South Carolina and Georgia, USA, 2014-2018.









