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SPECIAL SECTION

Assessing spatial ecological patterns of wild turkey relative abundance across North America

Muzi D. Sibiya[1] | Benjamin R. Goldstein[2] | Krishna Pacifici[2] | Roland Kays[3] | Michael V. Cove[3] | Alex J. Jensen[3] | William J. McShea[4] | Brittany M. Mason[5] | Corey T. Callaghan[5] | Marcus A. Lashley[6] | Carolina Baruzzi[7]

[1]Department of Wildlife Ecology and Conservation, Fort Lauderdale Research and Education Center, Institute of Food and Agricultural Sciences, University of Florida, Davie, FL 33314, USA

[2]Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC 27607, USA

[3]North Carolina Museum of Natural Sciences, Raleigh, NC 27601, USA

[4]Conservation Ecology Center, Smithsonian's National Zoo and Conservation Biology Institute, Front Royal, VA 22630, USA

[5]Department of Wildlife Ecology and Conservation, Institute of Food and Agricultural Sciences, Fort Lauderdale Research and Education Center, University of Florida, Davie, FL 33314, USA

[6]Department of Wildlife Ecology and Conservation, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL 32611, USA

[7]Department of Wildlife Ecology and Conservation, North Florida Research and Education Center, Institute of Food and Agricultural Sciences, University of Florida, Quincy, FL 32351, USA

Abstract

Land use dynamics compounded by climate change and landscape conversion continues to affect wildlife communities globally. Assessment of species experiencing widespread population declines across their occupied range is useful to understand both the effects of climate and land cover change. We jointly modeled observational data from camera traps and citizen science to assess effects of land cover and climatic variables on wild turkey (*Meleagris gallopavo*) relative abundance across the continental United States. We included spatially varying coefficients to account for the possibility that relationships among environmental features and wild turkey relative abundance vary across the species range. Our results suggest wild turkey relative abundance is marked by distinct spatial patterns across the United States with the greatest relative abundance located in the east and central United States, whereas the west is characterized by variability in relative abundance patterns. Spatially varying responses to climatic variables (mean maximum temperature and annual cumulative precipitation) and vegetation greenness had the strongest effects on relative abundance. Additionally, patterns of relative abundance of wild turkeys varied by ecological

Correspondence
Carolina Baruzzi, Department of Wildlife Ecology and Conservation, North Florida Research and Education Center, Institute of Food and Agricultural Sciences, University of Florida, 155 Research Rd, Quincy, FL 32351, USA.
Email: carolina.baruzzi@ufl.edu

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region; the eastern forests and Great Plains in the east and central United States exhibited the largest average relative abundance whereas western ecological regions had less dense and more spatially variable relative abundance. The strongest spatial variation in covariate effects was for temperature and precipitation, suggesting that wild turkeys may be adapting to local climatic conditions in ways that would be missed by a global habitat model. We found negative effects of mean maximum temperature and precipitation on wild turkey relative abundance that were strongest in the southern regions of the species range. Given the role of temperature and precipitation regimes highlighted in our study, climate change may pose significant concerns for wild turkeys in the southwest range.

KEYWORDS
citizen science, continental, integrated model, *Meleagris gallopavo*, SNAPSHOT

Land use and land cover changes continue to negatively affect wildlife communities (Fahrig et al. 2019). Particularly, pressure on wildlife communities increases as a result of loss or degradation of natural vegetation cover (McGuire et al. 2016, Young et al. 2016). Constraints on wildlife are further exacerbated by rapid climate change (McGuire et al. 2016). For example, increased stress from temperature changes poses challenges for wildlife to cope with additional stressors (Masson-Delmotte et al. 2021). Alternatively, rapid changes in temperature may hinder adaptation leading to population and species loss (Sinervo et al. 2010, Kerr et al. 2015). Similarly, changes in precipitation regimes can have direct and indirect effects on wildlife physiology and demography (e.g., Parent et al. 2016, Deguines et al. 2017). Tracking changes in animal populations or distribution patterns provides insights into how environmental change is affecting communities while allowing for informed conservation planning.

Wild turkey (*Meleagris gallopavo*) is a widespread and economically important game bird species in North America (Keck and Langston 1992). By the early 1900s, wild turkeys had significantly declined across their range due to market hunting, habitat loss, and degradation, but wild turkeys had successfully recovered following restocking efforts in the latter half of the century (Kennamer et al. 1992, McRoberts et al. 2014). However, recent studies focused on wild turkey abundance and population dynamics have documented declines across various regions of the United States (Ericksen et al. 2015, Byrne et al. 2016, Chamberlain et al. 2022, Londe et al. 2023). Studies suggest that variability in turkey abundance may be associated with factors such as land cover change (Nelson et al. 2023), changes in patterns of temperature and precipitation (Boone et al. 2023, Boone et al. 2024), and other factors such as predation and availability and quality of nesting cover (Thogmartin and Schaeffer 2000, Dreibelbis et al. 2008, Byrne et al. 2016). Although multiple potential causes have been identified, wild turkey abundance declines are likely driven by several compounding factors. As such, understanding the role of large-scale environmental conditions on wild turkey populations may provide critical information on the ongoing abundance dynamics.

Because wild turkey subspecies are characterized by somewhat unique geographical constraints and management-driven, site-specific conditions can have profound effects on local wild turkey populations, continental-scale declines may be influenced by large-scale factors (Streich et al. 2015, Pollentier et al. 2017, Chamberlain et al. 2022). Inference from most contemporary studies of wild turkey abundance is often limited to relatively small spatial scales and rely on limited data sets (but see Chamberlain et al. 2022, Londe et al. 2023). Thus, there is a need for repeatable methods of estimating the relative abundance of wild turkey at the continental scale while accounting for variation in relationships among wild turkey populations and various environmental factors. Fortunately, robust estimation of species distribution and abundance is increasingly achievable following recent developments in statistical software and growing capabilities of biodiversity models to effectively incorporate multiple data sources, including citizen-science data (Fletcher et al. 2019, Isaac et al. 2020, Mostert and O'Hara 2023).

Citizen science, characterized by public participation and crowdsourcing observations of species, is increasing the availability of contemporary ecological datasets, providing valuable information used to model wildlife distributions (Callaghan et al. 2021, Strebel et al. 2022, Baici and Bowman 2023). The contribution of crowdsourced data in wildlife management, including development of conservation policies, is increasing (Wyeth et al. 2020). Importantly, opportunistic citizen data fills existing gaps in structured surveys by observing biodiversity at expansive scales (Hadj-Hammou et al. 2017). Citizen-science data often suffer several biases resulting to unequal sampling across space and time; however, both citizen-science project managers and statistical modelers continuously develop protocols to minimize most biases (e.g., Kosmala et al. 2016). Citizen-driven observations may inform species distribution across spatiotemporal scales and researchers have successfully utilized citizen observations to describe species occupancy, relative abundance, and changes in populations (Iverson et al. 2024, White et al. 2024).

We developed continent-wide estimates of relative abundance associated with spatially varying environmental effects to improve our understanding of wild turkey occurrence across North America, guiding future management strategies for monitoring and addressing the ongoing wild turkey decline and promoting conservation efforts. We use data integration to jointly model citizen-science data with a robust, continent-wide, but spatially restricted camera-trap dataset collected under a standardized protocol. Our objectives were to 1) examine variability in relative abundance across the wild turkey range, 2) estimate spatial variability in the importance of covariates, and 3) assess regional estimates of relative abundance. In particular, we hypothesized that human density and climatic and habitat covariates will underlie wild turkey relative abundance throughout their range.

STUDY AREA

Our study area encompasses the conterminous part of North America, including the United States, within the native wild turkey range. Consequences of climate change differ among regions of the United States with the northern and eastern regions largely characterized by increasing precipitation while the southwest is getting drier (Groisman et al. 2004). Relative to the eastern United States, the west is dominated by semi-arid and arid landscapes. Additionally, while the mean annual temperature decreases latitudinally across the United States, measures of temperature also tend to decrease eastwards. Given such diverse ecosystems, the United States Environmental Protection Agency characterized North America into various ecoregions to facilitate management of natural resources (US EPA n.d., https://www.epa.gov/eco-research/ecoregions-north-america; Omernik 1987). For example, the level I characterization of ecoregions within the wild turkey range has 12 distinct ecosystems partitioned by similarities in biotic and abiotic factors. The effect of ecoregion on the distribution of wild turkey relative abundance is however less understood despite the potential for concerted efforts for the conservation of the species. Consequently, we aimed to assess variability in wild turkey relative abundance across distinct ecoregions.

METHODS

Data sources

We retrieved camera-trap observations of wild turkeys from 2 sources, the SNAPSHOT USA (2019–2023) and Carolina Critters (2016–2019) projects (Cove et al. 2021, Lasky et al. 2021, Kays et al. 2022, Shamon et al. 2024).

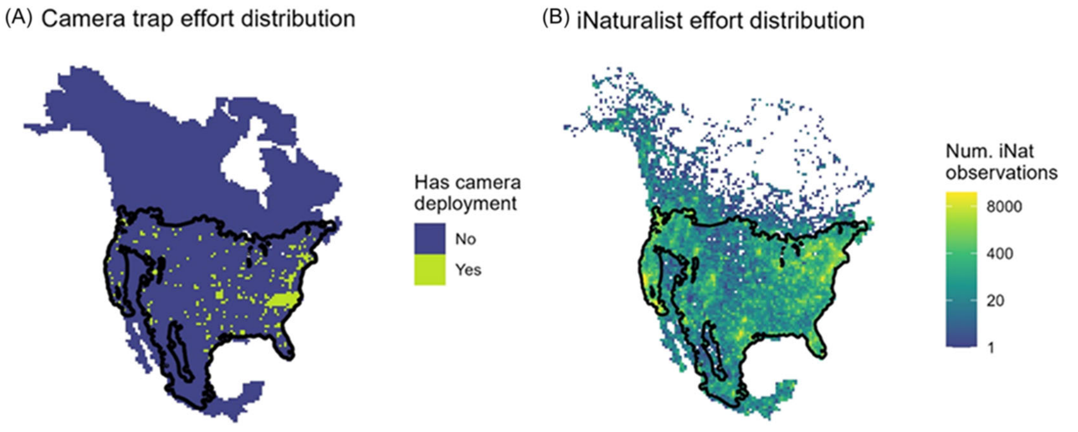

FIGURE 1 Distribution of observational data used to estimate the distribution of wild turkey in North America. Black line indicates the modeled range of wild turkey. (A) Locations of camera trap deployments from SNAPSHOT USA (years 2019–2023; Cove et al. 2021, Kays et al. 2022, Shamon et al. 2024) and Carolina Critters (years 2016–2019; Lasky et al. 2021). (B) Density of iNaturalist observations (years 2000–2022) of wild turkey detections as well as Galliformes and terrestrial mammals (to inform potential non-detections of wild turkey), summarized on a 50-km grid.

We retained data from 10,436 unbaited cameras (Figure 1A). We constructed detection histories using 10-day windows (i.e., to define sampling occasions within each camera) where, for each window j associated with deployment i, we recorded the observation y_{ij} = 1 if a wild turkey was detected in that 10-day period and y_{ij} = 0 otherwise (Goldstein et al. 2024).

We retrieved citizen-science observations of wild turkey from iNaturalist, an opportunistic species observation reporting platform that encourages participants to upload media such as photos and audio files to facilitate species identification of various taxa (iNaturalist n.d., https://www.inaturalist.org). iNaturalist allows robust vetting of observations (such as distinguishing wild turkey subspecies including the domestic turkey, which was removed from our dataset) by experienced users and vetted observations are thereafter classified as research grade. In our analysis, we used only research grade observations. To account for sampling effort of wild turkey from iNaturalist, we included sampled observations of terrestrial mammals and birds in the family Galliformes in North America from the iNaturalist participatory science repository in June 2024 (doi.org/10.15468/dl.khcarb). The original dataset contained 1.9 million observations that occurred between 20 June 1900 and 31 December 2022. We retained 1,778,280 unique research grade observations that occurred during 1 January 2000 to 31 December 2022, excluding observations marked as tracks or scat. Of these observations, 75,560 were detections of wild turkey (Figure 1B) that did not consider demographic information as iNaturalist observations typically lack such details. The rest of the observations represented potential non-detections of wild turkey (i.e., from mammals and Galliformes observations other than wild turkey sightings).

Spatial covariates

We retrieved 9 spatial covariates hypothesized to influence wild turkey distribution based on published literature, which we summarized to a 5-km grid. The 9 covariates were: 1) annual maximum temperature (Vega et al. 2017); 2) annual cumulative precipitation (Vega et al. 2017); 3) mean enhanced vegetation index that describes vegetation greenness (mean EVI; Didan 2021); 4) annual variability in enhanced vegetation index (greatest monthly EVI minus lowest monthly EVI; Didan 2021); 5) percent grassland (Jung et al. 2020); 6) percent agriculture (Jung et al. 2020); 7) percent wetland (Jung et al. 2020); 8) human population density (CIESIN 2018); and 9) terrain roughness

(Amatulli et al. 2018). For the agriculture variable, we combined the arable and pastureland classes from Jung et al. (2020), following their grouping of these classes into the larger artificial category (Figure S1, available in Supporting Information).

We also retrieved 2 spatial covariates hypothesized to influence camera-trap detection probabilities - distance to the nearest road (Meijer et al. 2018) and canopy height (Potapov et al. 2021), which we estimated at each camera. For canopy height, the value of 0 was specified for cameras that were not under forest canopy. We confirmed that our covariates were not multicollinear across the study region by calculating variance inflation factors (VIFs) for the covariates set. All VIFs were <4. We employed a square-root transformation to human population density then centered and scaled all continuous covariates prior to analyses.

Statistical analysis

We restricted the model to the North American range of wild turkey, which we defined as the IUCN range extended by observations from camera traps and iNaturalist (IUCN 2023). We extended the range by creating 50-km buffers around all iNaturalist and camera-trap detections of wild turkey outside the IUCN range, then dissolving the buffers into a single polygon and excluding observations >50 km away from this polygon.

We constructed a spatially explicit hierarchical integrated species distribution model to estimate the relationship between wild turkey relative abundance and 9 spatial covariates (Table 1; Koshkina et al. 2017, Pacifici et al. 2017, Miller et al. 2019). The model uses an inhomogeneous point process framework to model both camera-trap detections and iNaturalist reporting rates of wild turkey as following a shared underlying intensity process.

We calculated the latent intensity (which describes relative abundance) on a 5-km grid encompassing the modeled range of wild turkey. For each 5-km cell s, intensity λ_s was

$$\log(\lambda_s) = \beta_0 + x_s^T \beta_{g(s)} + \epsilon_{g(s)}$$

$$\epsilon_g \sim CAR\left(0,\ \sigma_\epsilon^2\right)$$

where β_0 was an intercept, x_s^T was a vector of 9 covariates, $\beta_{g(s)}$ were the spatially varying effects of the covariate, and $\epsilon_{g(s)}$ was a spatially structured conditional autoregressive effect defined on a 100-km grid across the range of wild turkey, where $g(s)$ indexed the 100-km cell g containing the relevant 5-km cell s.

The effect of the kth covariate on intensity in 100-km cell g, β_{kg}, was defined as

$$\beta_{kg} = \beta_{k0} + \gamma_{k1}\, \beta_{ke1} + \gamma_{k2} \beta_{kg2}$$

where,

$$\beta_{ke1} \sim N\left(0,\ \sigma_{\beta 1}^2\right)$$

$$\beta_{kg2} \sim CAR\left(0,\ \sigma_{\beta 2}^2\right)$$

$$\gamma_{ka} \sim Bernoulli\,(\pi_a)\ \text{for}\, a \in 1, 2$$

meaning that a given β_{kg} was the sum of a spatially constant mean effect β_{k0}, an ecoregion-level random slope β_{ke1}, and a conditional autoregressive random process β_{kg2}. The switching variables γ_{k1} and γ_{k2} allowed each spatially varying component to be potentially turned off (when $\gamma_{ka} = 0$), and the posterior distributions of γ_{ka} can be interpreted as the posterior probability that the covariate effect β_{kg} varied according to spatial process a.

TABLE 1 The climatic, landscape, human development, and detection covariates used in a hierarchical integrated species distribution model to investigate relative abundance of wild turkey across the species range in North America. Shown are units, temporal coverage, spatial resolution (res), and data sources.

Type	Covariate (unit)	Year (res)	Reference
Climatic	Annual maximum temperature (0.1°C)	2000–2010 (10 m)	Vega et al. (2017)
	Annual cumulative precipitation (mm)	2000–2010 (10 m)	Vega et al. (2017)
Landscape	Mean enhanced vegetation index	2015 (1 km)	Didan (2021)
	Annual variability in enhanced vegetation index	2015 (1 km)	Didan (2021)
	Grassland (%)	2015 (100 m)	Jung et al. (2020)
	Wetland (%)	2015 (100 m)	Jung et al. (2020)
	Terrain roughness (%)	2000 and 2010 (1 km)	Amatulli et al. (2018)
Human development	Agriculture (%)	2015 (100 m)	Jung et al. (2020)
	Human population density (No. people/km^2)	2000–2020 (~1 km)	CIESIN (2018)
Camera-trap detection	Log-scale distance to nearest road (km)	1997–2015 (~1 km)	Meijer et al. (2018)
	Canopy height (m)	2019 (30 m)	Potapov et al. (2021)

Camera-trap detections follow an occupancy model defined by the following equations:

$$y_{ij} \sim Bernoulli\,(z_i\, p_{ij})$$

$$z_i \sim Bernoulli\,(\psi_i)$$

$$cloglog\,(p_{ij}) = w_{ij}^T \alpha_w + x_{s(i)}^T \alpha_x + m_{l(i)}$$

$$m_l \sim N\left(0, \sigma_m^2\right)$$

where z_i was the latent state with probability ψ_i describing whether a wild turkey used the area surveyed at any point during deployment i and p_{ij} was the probability of detecting a wild turkey given that it uses the area surveyed by the camera. The probability p_{ij} was a complementary-log-log-scale linear combination of detection-level covariate data w_{ij}^T - specifically, day of year, day of year squared, canopy height, and distance to road - with effects coefficients α_w; 9 spatial covariate data $x_{s(i)}^T$ with effects coefficients α_x; and a random effect of location $m_{l(i)}$, shared by deployments at the same location in different years. The camera-use probability ψ_i was directly linked to the shared latent point process intensity as

$$cloglog\,(\psi_i) = \log\ (\lambda_{s(i)})$$

where $\lambda_{s(i)}$ was the latent intensity in the 5-km cell s containing deployment i.

The iNaturalist data were modeled according to a negative binomial generalized linear mixed model with an offset to account for variability in sampling effort. The observed count in 50-km cell c, N_c, was modeled as

$$N_c \sim NegativeBinom\,(\mu_c E_c,\ \phi)$$

$$\log(\mu_c) = \theta_0 + \theta_1 \log\left(\sum_{s \in c} \lambda_s\right)$$

where μ_c was the expected number of wild turkey observations per unit effort; E_c was the level of iNaturalist effort (total observations of all mammals and Galliformes) in cell c, observed directly in these data; ϕ was an overdispersion parameter, and θ_0 and θ_1 defined the strength of the relationship between the intensity field (summed across cells s within iNaturalist aggregation cell c) and iNaturalist data. This modeling approach weakened the relationship between iNaturalist data and the underlying intensity process, allowing the 2 datasets to potentially diverge.

We fit the model using Markov Chain Monte Carlo (MCMC) with NIMBLE version 1.2.0 and used the reversible jump MCMC sampler in NIMBLE to support estimation of spatially varying coefficient switching variables (de Valpine et al. 2017). We fit the model for 10 chains of 10,000 iterations each including a burn-in period of 2,000 iterations. To assess convergence, we monitored the log probability of the observed data, $\boldsymbol{y}$ and $\mathbf{N}$, and calculated the Gelman-Rubin diagnostic, which indicated convergence at <1.1. We interpreted the posterior distributions of each β_{kg} to understand the spatially varying effect of each covariate on wild turkey relative abundance. To characterize how the relative importance of each covariate changed in space, we identified which covariate had the greatest magnitude in each cell across posterior samples and refer to the covariate that is most often of the greatest magnitude as the dominant covariate in that cell. After model fitting, we calculated posterior distributions for the mean relative abundance in each ecoregion as the posterior averages of all λ_s values in the ecoregion. To characterize model predictive performance, we chose a subset of 20% of cameras used to fit the model and calculated the Brier score, the average squared error in predicted observations (a function of detection and camera use probability) with respect to observed data (Gneiting and Raftery 2007).

RESULTS

Wild turkeys exhibited distinct patterns of relative abundance across North America with the largest proportions being concentrated in the eastern and central United States (Figure 2). Notable hot spots existed in areas within the midwest and the southeast. In general, the western United States and parts of Mexico displayed markedly lower relative abundance patterns (Figure 2). The associated uncertainty for relative abundance estimate was minimal in areas of high relative abundance, indicating robust model predictions, while it increased in areas with lower predicted relative abundance, suggesting variability in the data or environmental conditions (Figure S2, available in Supporting Information). The mean posterior estimate of θ_1, which controlled the linear correspondence between observed counts in iNaturalist, was 0.319 (95% CI: 0.268–0.379), suggesting that these data showed a consistent positive correlation between iNaturalist reporting rates and camera-trap occupancy probability. The posterior mean Brier score was 0.05, suggesting good model fit (Table S1, available in Supporting Information).

Analysis of habitat covariates revealed significant spatial variability in factors influencing wild turkey relative abundance across North America (Figure 3A). Key covariates driving wild turkey relative abundance included mean EVI, precipitation, maximum temperature, and human population density, with maximum temperature and mean EVI showing the largest overall effects (Figure 3B). Precipitation and terrain roughness also contributed notably but with less spatial consistency. Dominant influence of covariates varied among areas across the wild turkey range (Figure 4). For example, mean EVI had the strongest positive influence in the western range while maximum temperature was positively and negatively associated with the relative abundance of wild turkey in the north and southwest areas of their range, respectively (Figure 4A, E). On the other hand, human population density was negatively associated with the species relative abundance across its southern range whereas spatial variability in precipitation had similar influence except for a strong positive association in the west (Figure 4C, D).

Estimates of wild turkey relative abundance varied markedly among ecoregions with estimates tending to be largest in the eastern tropical forests and Great Plains while remaining lowest in the wet or dry forests and deserts (Figure 5B). Likewise, some covariates exhibited strong contrasting effects across ecoregions (Figure S3, available in

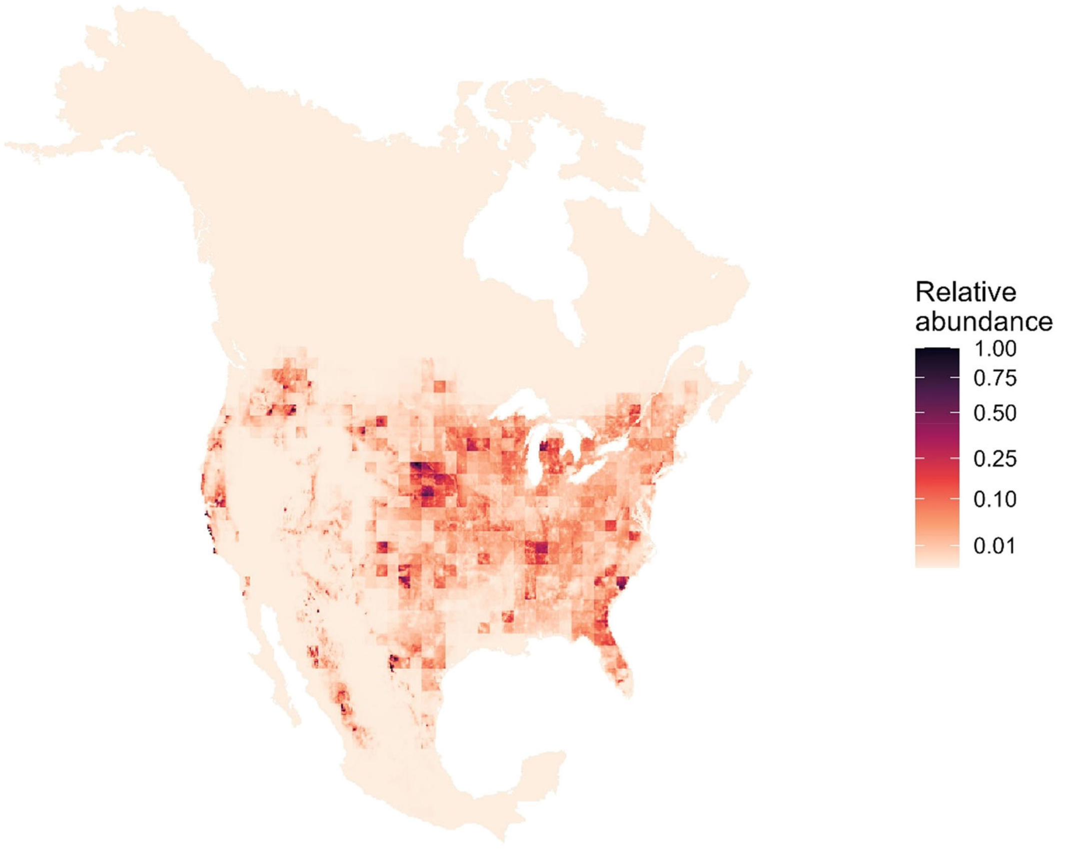

FIGURE 2 Predictions from our model of wild turkey relative abundance throughout North America using camera trap data from SNAPSHOT USA (years 2019–2023) and Carolina Critters (years 2016–2019) and iNaturalist observations (years 2000–2022). Relative abundance was scaled to the range 0–1, censoring outlier cells above the 99.99th quantile. The color ramp uses a square root scale for visualization.

Supporting Information). Specifically, inconsistent covariates included terrain roughness, maximum temperature, and precipitation. Other than the 3 strongly contrasting covariates mentioned above, the rest of the covariates mostly influenced consistent patterns of wild turkey relative abundance across the 11 ecoregions (Figure S3, available in Supporting Information). For example, spatial variation in the effect of wetlands on relative abundance of wild turkey was generally negative. Grasslands and mean EVI on the other hand, had generally positive influence on wild turkey relative abundance. Conversely, human population density exhibited consistent negative effects of relative abundance. At the ecoregion scale, both agricultural landscapes and variability in EVI tended to weakly associate with variation in wild turkey relative abundance (Figure 5B; see Table S1, available in Supporting Information, for a list of all model parameters).

DISCUSSION

We produced estimates of wild turkey relative abundance throughout their entire range in North America. Relative abundance estimates were largest in the east and central United States, geographic areas dominated by 3 turkey subspecies (eastern, *M. g. silvestris*; Merriam's, *M. g. merriami*; and Rio Grande, *M. g. intermedia*; Chamberlain et al. 2022). However, patterns of relative abundance in the east and central areas were characterized by various

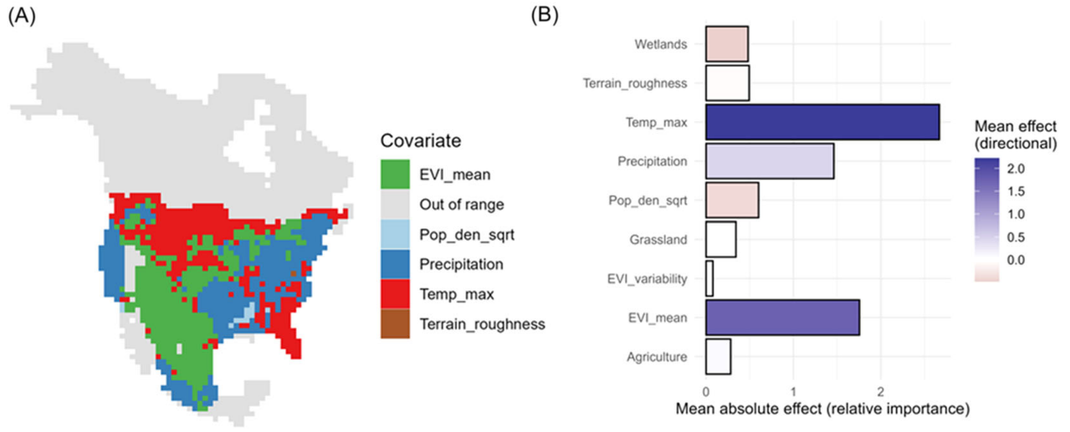

FIGURE 3 Spatial variability and importance of habitat covariates influencing wild turkey relative abundance across North America. (A) Map displaying the dominant covariate: mean enhanced vegetation index (EVI_mean), maximum temperature (Temp_max), precipitation, human population density (Pop_den_sqrt), and areas out of range. (B) Bar plot showing the overall absolute effect (relative importance) of key covariates on wild turkey relative abundance. Covariates are ranked by their mean effect, with maximum temperature and mean EVI identified as the most influential factors across the species' range.

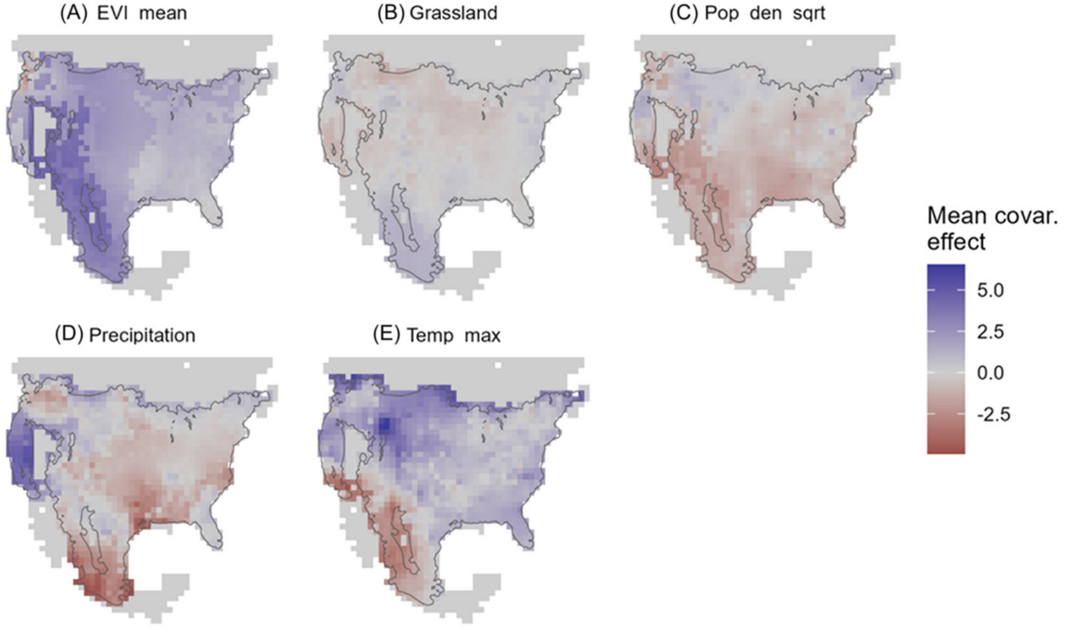

FIGURE 4 Mean (per 100-km cell) effect of the covariates (Mean covar. effect) on wild turkey relative abundance across North America, displaying the mean effect of (A) mean enhanced vegetation index (EVI mean), (B) grasslands, (C) human population density (Pop den sqrt), (D) precipitation, and (E) maximum temperature (Temp max).

estimates with certain locations showing very few or no wild turkeys. Variation in the observed patterns of wild turkey relative abundance are likely a result of habitat degradation and loss across the 2 geographical areas (Davis et al. 2018). Conversely, the western United States and parts of Mexico showed markedly low measures of relative abundance, suggesting limited habitat availability in these more semi-arid regions.

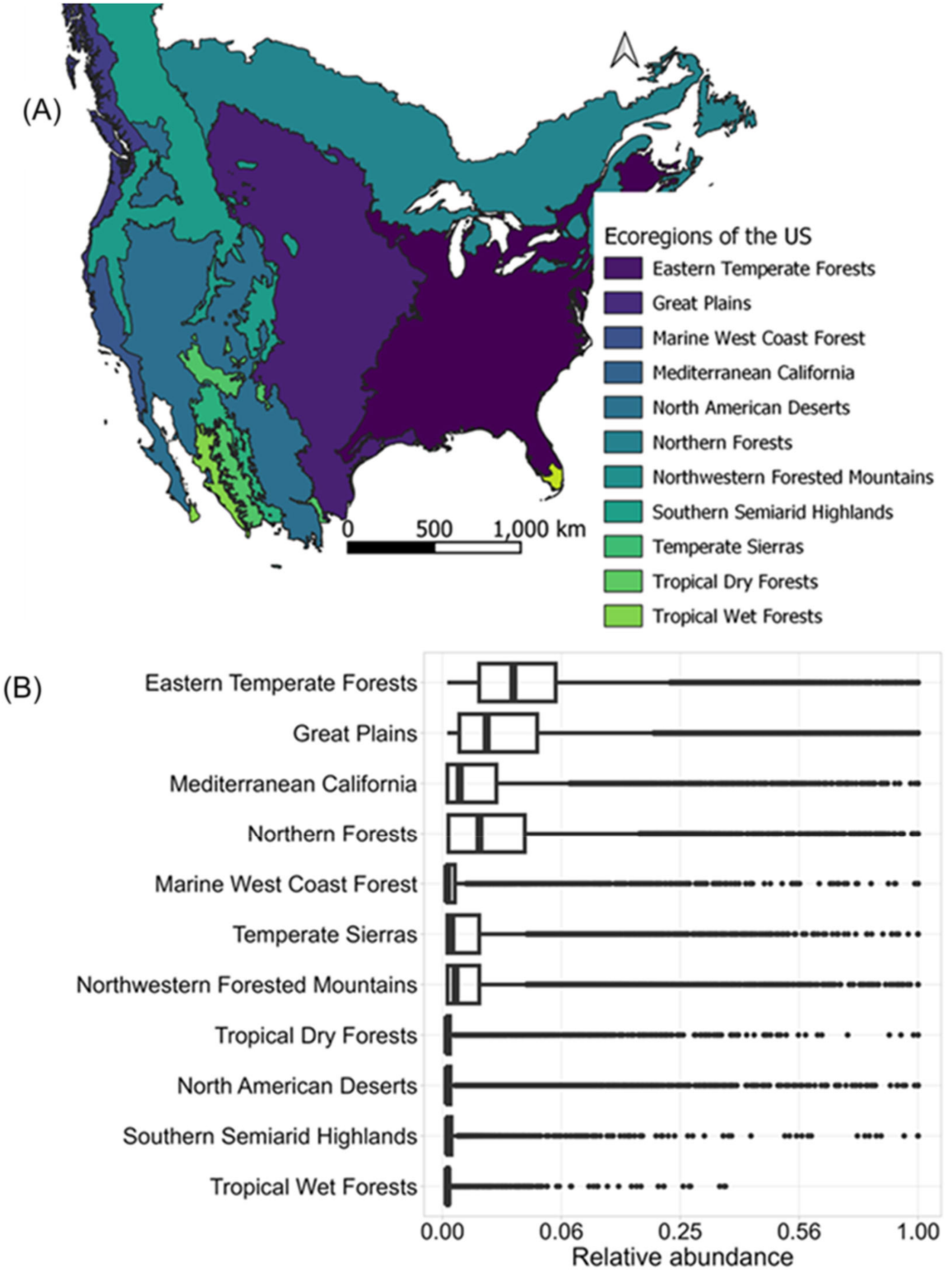

FIGURE 5 (A) Eleven level 1 Environmental Protection Agency ecoregions of the United States and (B) mean estimates of relative abundance of wild turkey across the 11 level 1 ecoregions of the United States. Relative abundance was scaled to the range 0–1, censoring outlier cells above the 99.99th quantile.

Our analysis suggests that annual maximum temperature and annual cumulative precipitation are associated with increased variation in wild turkey relative abundance. Even though increasing maximum temperatures showed less distinct effects on wild turkey relative abundance in the eastern forest and south of the Great Plains, negative associations were apparent in the southwest. Precipitation had similar effects but over an extended area especially in the southern range. Boone et al. (2024) focused on effects of temperature anomalies and precipitation on eastern wild turkeys, showing that the effects of temperature anomalies vary depending on phenology. For example, during incubation, daily nest survival increased with positive temperature anomalies. However, negative temperature anomalies prior to nesting (i.e., January) were more strongly associated with nest survival, which highlights the role of more fine-scale temperature patterns influencing various dynamics related to plant productivity and female stress. In contrast, in our study, maximum temperature had a negative association with wild turkey relative abundance in the west-southern range (e.g., North American deserts and temperate Sierras), suggesting the potential for high temperatures to limit the southern range of the species in North America. Precipitation also had a strong, negative effect across most southern ecoregions, which may be caused by mismatches between nesting and resource availability, decreased nest success due to flooding, or increased predation as a result of increased scent detection by predators (Conover 2007, Fisher et al. 2015, Boone et al. 2023). The southwest region is dominated by the Gould's (*M. g. mexicana*) and Rio Grande wild turkey subspecies that rely heavily on the riparian ecosystems within the region for thermoregulation and hydration (Rakowski et al. 2019, Cohen et al. 2022). On the other hand, spatial variability in precipitation had a strong positive effect on wild turkey relative abundance adjacent to the Pacific Coast. However, with recent findings suggesting declining precipitation regimes together with increasing urbanization across this region, the positive precipitation-turkey relative abundance association would likely be undermined in the near future (Underwood et al. 2009, Deitch et al. 2017).

Vegetation characteristics were also strong drivers of wild turkey relative abundance. In particular, associations with mean EVI across the western range of the species including parts of the central United States suggest that patches with some canopy cover promote wild turkey relative abundance, which supports the findings of numerous other studies showing the importance of forest cover for wild turkey (Pollentier et al. 2017, Davis et al. 2018, Tyl et al. 2023). The lack of general effects of grasslands on wild turkey relative abundance should not be interpreted as an indication of their overall lack of importance as open vegetation types are essential for wild turkeys during nesting and brood-rearing life stages (e.g., Little et al. 2016, Chamberlain et al. 2020, Nelson et al. 2023). Our grasslands covariate includes grasslands burned at different intervals, which should represent various levels of wild turkey habitat quality that together have little net effect. Moreover, grassland-wild turkey associations may be confounded by other factors such as species composition, as non-native grasses are considered a poor-quality resource for wild turkeys (Barnes et al. 2013, Harper et al. 2021, Johnson et al. 2022).

Given effects of human population, climate, and habitat on wild turkey abundance, ongoing global changes are likely to pose substantial challenges for wild turkey populations. Compounding effects of relatively large density of human populations in the west and parts of the southeast range paired with habitat degradation and climate anomalies will likely exacerbate one another (Miller and Miller 2004, Spears et al. 2007, Underwood et al. 2009). For example, persistent droughts may alter wild turkey habitat, diminishing vegetation cover within areas such as the southwestern United States and potentially increasing wild turkey exposure to predation and extreme weather conditions (Cook et al. 2015, EL-Vilaly et al. 2018). Addressing these interconnected issues, likely from a habitat standpoint, will be critical for wild turkey conservation.

Wild turkey population dynamics may be influenced by a suite of factors and, given the species consist of various subspecies occupying somewhat unique landscapes, it would be challenging to exhaustively characterize range-wide population limiting factors. For example, unmeasured factors such as hunting pressure, historic conservation reintroductions, hybridization with domestic turkeys, predation, survival, snow cover, and other human effects such as timber harvesting and mismanagement of fires could be driving subspecies population distribution. Hunting for example, may have contrasting effects on wild turkey populations (Scott and Boeker 1975, Lafon and Schemnitz 1995, Hughes et al. 2005, Pollentier et al. 2021, Lashley et al. 2025). While it can encourage habitat conservation and sustainable harvesting, failure to adhere to state regulations and science-based management practices would likely have negative effects on population trends. Nevertheless, wild turkey subspecies exhibit some overlap in their habitat requirements (Rumble and Anderson 1992) and by i) integrating various data sources (that is increasingly viewed as a critical technique to producing robust species distribution estimates [e.g. Fletcher et al. 2019]), ii) simultaneously predicting spatially varying coefficients for climatic or landscape variables and human development, and iii) assessing the species range-wide effects, we provide crucial information that may be used during wild turkey reintroduction efforts across North America. Essentially, over the years, agency or state biologists data have yielded somewhat inconsistent trends in wild turkey population dynamics marked by surprising changes in population dynamics, such as a 3-fold increase in population abundance between 1994 and 1999, likely driven by lack of a standardized data collection protocol among states and use of an imperfect formula to estimate population abundance (Kennamer and Kennamer 1995, Tapley et al. 2000, Chamberlain et al. 2022).

CONSERVATION IMPLICATIONS

Given that maximum temperature and mean EVI had the greatest overall effects on wild turkey relative abundance, considering climatic and habitat effects across state boundaries is essential for wild turkey population management and such information may provide critical insights for state or federal agencies that manage and restore wild turkey habitat locally and regionally. Cross-state efforts are critical in promoting wild turkey conservation, and ecoregion-level effects observed in this study suggest the potential for tailored efforts aimed at land cover management. For example, federal, state, and nonprofit agencies working within the eastern forests may collaborate to simultaneously address habitat loss and fragmentation by enhancing restoration efforts and advocating for the development of wildlife corridors. Because the negative associations of human population density observed in this study may be a proxy for other anthropogenic pressures, as the east and central United States continue to experience increasing human populations, development of strong environmental policies aimed at minimizing land use intensification within these 2 geographical areas would bolster ongoing efforts to manage wild turkey abundance. Importantly, broad-scale conservation efforts to enhance wildlife connectivity may be critical for the conservation of wild turkey. Finally, to promote wild turkey populations across the western United States, native vegetation cover in most landscapes should be restored and maintained. Indeed, although some areas may be identified as areas of relatively large wild turkey abundance in our model, fine-scale habitat characteristics, such as those generated by frequent fires, were not captured in our model. As such, recent trends in degrading habitat resulting from fire suppression or the underuse of other wildlife habitat management practices should still be one of the priorities for wild turkey conservation (Harper et al. 2016, Hanberry et al. 2020, Alexander et al. 2021).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

This study did not involve any direct interaction with or experimentation on animals. All data analyzed were obtained from publicly available sources. As such, no ethical approval or specific permissions were required for data collection. No animals were harmed in the course of this research.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. Data was also retrieved from GBIF.com (GBIF n.d.), a public domain.

ORCID

Muzi D. Sibiya https://orcid.org/0000-0003-0360-6780
Marcus A. Lashley https://orcid.org/0000-0002-1086-7754

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