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Research Paper

Examining the potential impacts of geolocators on a small migratory songbird, the Golden-cheeked Warbler: results from a multi-year study

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ABSTRACT. Advancements in tracking technologies have improved our knowledge of migratory movements for many songbirds and simultaneously raised questions about how tracking devices may influence an individual's survival and behavior. During a five-year study (2017–2021) at two study sites in central Texas, USA, we quantified the potential impacts of miniaturized light-level geolocators on a small (~10 g) Nearctic-Neotropical migratory songbird, the Golden-cheeked Warbler (*Setophaga chrysoparia*; hereafter warbler). We used generalized linear models to examine the effects of geolocator, age, and year on warbler pairing success, fledging success, and apparent annual return rates (hereafter return rates) at each study site. Most parameters we considered in our pairing success, fledging success, and return rate models were not statistically significant. However, at one study site, we found lower return rates for second year warblers with geolocators compared to second year and after second year warblers without geolocators. We also described warbler behavior immediately after we attached the geolocators, body condition upon their return, and body mass before and after carrying the devices. Most warblers resumed normal activities (e.g., singing, foraging) within 30 min after we attached the devices, showed no visible signs of injuries, and had similar body mass before and after carrying the geolocators. Overall, we did not find consistent evidence across sites or age classes that miniaturized light-level geolocators negatively impacted the Golden-cheeked Warbler responses we measured. However, we encourage continued research on this topic, especially as it relates to age-dependent effects of geolocator attachment on birds.

Effets potentiels de géolocalisateurs sur un petit passereau migrateur, la Paruline à dos noir : résultats d'une étude pluriannuelle

RÉSUMÉ. L'avancée constante des technologies de suivi a permis aux chercheurs d'étoffer leurs connaissances sur les déplacements migratoires de nombreux passereaux et, simultanément, a soulevé des questions à propos de l'effet de ces dispositifs de suivi sur la survie et le comportement des individus. Durant cinq ans (2017-2021) sur deux sites d'étude dans le centre du Texas, aux États-Unis, nous avons quantifié les effets potentiels de géolocalisateurs miniaturisés enregistrant la luminosité ambiante sur un petit passereau migrateur néarctique et néotropical (~10 g), la Paruline à dos noir (*Setophaga chrysoparia*; ci-après paruline). Nous avons utilisé des modèles linéaires généralisés pour examiner les effets du géolocalisateur, de l'âge et de l'année sur le succès d'appariement de la paruline, le succès de l'envol et les taux de retour annuels apparents (ci-après les taux de retour) à chaque site d'étude. La plupart des paramètres pris en compte dans nos modèles de succès d'appariement, de succès d'envol et de taux de retour n'étaient pas statistiquement significatifs. Cependant, sur un site d'étude, nous avons obtenu des taux de retour plus faibles pour les parulines de deuxième année munies d'un géolocalisateur par rapport aux parulines de deuxième année et après la deuxième année sans géolocalisateur. Nous avons également décrit le comportement des parulines immédiatement après la pose des géolocalisateurs, leur état corporel à leur retour et leur masse corporelle avant et après le port de géolocalisateurs. La plupart des parulines ont repris leurs activités normales (p. ex. chant, recherche de nourriture) dans les 30 minutes qui ont suivi la pose des dispositifs, n'ont montré aucun signe visible de blessures et avaient une masse corporelle similaire avant et après avoir porté un géolocalisateur. Dans l'ensemble, nous n'avons pas trouvé d'indices cohérents entre les sites ou les classes d'âge indiquant que les géolocalisateurs miniaturisés enregistrant la luminosité ont eu un effet négatif sur les comportements de la Paruline à dos noir que nous avons mesurés. Toutefois, nous encourageons la poursuite de recherches sur ce sujet, en particulier en ce qui a trait aux effets de l'attachement du géolocalisateur sur les oiseaux en fonction de leur âge.

Key Words: *fledging success; Golden-cheeked Warbler; light-level geolocator; pairing success; return rate; Setophaga chrysoparia; Texas*

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INTRODUCTION

Advancements in tracking technologies have improved our knowledge of migratory behavior for many songbirds, including the timing, location, and duration of migration, as well as the linkages of individuals or populations between different stages of their annual cycles (i.e., migratory connectivity; Marra et al. 2006, Cohen et al. 2018, Hill and Renfrew 2019). However, increased use of tracking devices on songbirds has simultaneously raised questions about how these devices may affect songbird behavior (e.g., Brlík et al. 2020), body condition (e.g., Peterson et al. 2015), flight performance (e.g., Bowlin et al. 2010), phenology (e.g., de Zwaan et al. 2019), reproductive success (e.g., Raybuck et al. 2017a), and survival (e.g., Blackburn et al. 2016). Studies that explore this topic are necessary to guide and promote the safe and ethical use of tracking devices by researchers (Geldart et al. 2022) and to minimize potential biases in tracking data (Jewell 2013), especially as we expand our ability to track increasingly smaller species.

One device that has gained popularity for tracking long-distance avian movements is the archival light-level geolocator (hereafter geolocator). Geolocators record light intensities at regular time intervals, and researchers can use the stored data to estimate the latitude and longitude of an individual's location (Hill and Braun 2001, Ekstrom 2004, Stutchbury et al. 2009). Geolocators are not without limitations, as individuals must be relocated and recaptured to retrieve the data and these devices do not have the same precision as other tags (e.g., Global Positioning System [GPS], satellite transmitters; Bridge et al. 2013, McKinnon and Love 2018). However, geolocators represent one of the only low-cost, lightweight options for tracking long-distance movements of small migratory species (Bridge et al. 2013, McKinnon and Love 2018) and have provided important insight into the movement ecology of songbirds that was previously unknown, including migration routes (e.g., Salewski et al. 2013), within-season movements (e.g., Heckscher et al. 2015), and overwintering locations (e.g., Cooper et al. 2017).

Several studies have explored the potential impacts of geolocators on passerines and non-passerines. As found with other tracking devices (Geen et al. 2019, Geldart et al. 2022), the results of such studies have been mixed and depend on many factors, including species, environmental conditions at the time of attachment, tag type, and attachment methods. A meta-analysis conducted by Costantini and Møller (2013) with species that represented different body sizes, migration distances, foraging behaviors, and attachment methods found that geolocators negatively affected survival; that the effect size was larger for aerial foragers than other species; and that leg band attachments were more detrimental to birds than the leg-loop backpack harness. Later, a meta-analysis for birds weighing < 100 g conducted by Brlík et al. (2020) found no evidence that geolocators negatively impacted breeding performance, body condition, or phenology. However, the authors did find a weak negative impact of geolocators on apparent survival (defined as recapture or reencounter rate depending on the study) that was stronger with increasing relative load of the geolocators, when geolocators were attached with elastic harnesses, and for smaller-bodied species.

Miniaturized geolocators (0.3 g) have now been used to study the movement ecology of birds as small as 6 g. Geolocators negatively impacted return rates of ~9 g Cerulean Warblers (*Setophaga cerulea*; Raybuck et al. 2017a, but see Raybuck et al. 2017b and Streby and Kramer 2017), 9–11 g Common Yellowthroats (*Geothlypis trichas*; Taff et al. 2018), and 6–9 g Prairie Warblers (*S. discolor*; Campbell et al. 2021). Conversely, Peterson et al. (2015) found no evidence that geolocators negatively impacted return rates of 8–10 g Golden-winged Warblers (*Vermivora chrysoptera*) and Delancey et al. (2020) found similar results for ~9 g Cerulean Warblers. Beyond return rates, Raybuck et al. (2017a) found that geolocators did not impact within-season survival, nest survival, or provisioning rates of Cerulean Warblers; Campbell et al. (2021) found that geolocators did not influence inter-annual territory fidelity (i.e., distance between territory locations from one year to the next); and Peterson et al. (2015) found no difference in return rates of individuals carrying stalkless (light sensor is positioned on the unit) or stalked (light sensor is elevated above the unit) geolocators.

Most movement data we need to inform conservation, management, and policy decisions for small songbirds would be impossible to collect without the miniaturization and use of geolocators. However, quantification and reporting of the potential effects that geolocators have on a wide variety of species, especially small-bodied birds, is necessary to maximize the benefits of movement studies and to minimize potential harm. From 2017 to 2021, we deployed and retrieved geolocators on male Golden-cheeked Warblers (*Setophaga chrysoparia*) at five study sites in Texas, USA to examine the species' movements during non-breeding periods. The Golden-cheeked Warbler is an 8–12 g endangered Nearctic-Neotropical migrant that breeds in Ashe juniper (*Juniperus ashei*) woodlands in central Texas, USA (Pulich 1976, Ladd and Gass 2020, Long et al. 2021) and overwinters in southern Mexico and Central America (Rappole et al. 1999, Komar et al. 2011, Ladd and Gass 2020). Their migration routes were unknown prior to our movement study (see Long et al. 2023, Macey 2023), but given their small size, high annual return rates (24–67%; Groce et al. 2010, Macey and Collins 2022), strong site fidelity (Jetté et al. 1998, Maas-Burleigh 1998), and high recapture rates (> 75%; J. Macey, *personal observation*), Golden-cheeked Warblers were a good candidate for a tracking study with geolocators. The information we gained was critical to understanding the full life cycle ecology of Golden-cheeked Warblers and could help inform conservation planning for this species.

During this larger movement study, we examined the potential effects of geolocators on Golden-cheeked Warbler pairing success, fledging success, and apparent annual return rates (hereafter return rates) at two study sites. We included age and year in our generalized linear models because these factors can influence Golden-cheeked Warbler responses (e.g., Marshall 2012, Pruett et al. 2017). We also described Golden-cheeked Warbler behavior immediately after we attached the geolocators (i.e., observations of flight and balance), body condition upon their return, and body mass before and after carrying the devices. The study sites we used for this research were monitored in previous years using similar methods, providing us with baseline data to aid in the interpretation of our results. We predicted that males with and without geolocators would resume normal activities (e.g., foraging, singing, preening) following handling and would remain on site for the rest of the breeding season

(Hayden et al. 2008, Trumbo et al. 2021). We did not expect the geolocators to negatively impact male pairing or fledging success (Peterson et al. 2015, Raybuck et al. 2017a, Brlík et al. 2020), but we predicted that geolocators could have a negative effect on male return rates (Barron et al. 2010, Arlt et al. 2013, Brlík et al. 2020).

METHODS

Study sites

We conducted our research at U.S. Army Fort Cavazos (hereafter Fort Cavazos or FC; formerly Fort Hood) and Joint Base San Antonio-Camp Bullis (hereafter Camp Bullis or CB) in central Texas. Fort Cavazos (31.1397°N, 97.7658°W) was located along the eastern edge of the Edwards Plateau in Bell and Coryell counties, which occurs in the Cross Timbers ecological region of Texas (Griffith et al. 2007). The total area of FC was 86,994 ha, which included ~20,018 ha of Golden-cheeked Warbler habitat (Macey and Collins 2022). Elevation at FC ranged from 152 to 349 meters above sea level (masl; USGS 2024). Based on 30-year averages (1991–2020), minimum and maximum monthly temperatures in the region ranged from 2 °C in January to 36 °C in August and total annual precipitation was 88 cm (Palecki et al. 2021). Camp Bullis (29.6833°N, 98.5667°W) was located north of San Antonio in Bexar and Comal counties, near the intersection of the Blackland Prairies, Edwards Plateau, and South Texas Plains ecoregions in Texas (Griffith et al. 2007). The total area of CB was 11,287 ha, which included ~6144 ha of Golden-cheeked Warbler habitat (Ley and Davis 2022). Elevation at CB ranged from 314 to 455 masl (USGS 2024). Based on 30-year averages, minimum and maximum monthly temperatures in the region ranged from 5 °C in January to 36 °C in August and total annual precipitation was 82 cm (Palecki et al. 2021).

We conducted our research on three plots at each study site. At FC, plots included: a 71-ha plot located on the west side of the base that has been continuously monitored since 2003, a 100-ha plot located on the northeast portion that has been continuously monitored since 2016, and a 72-ha plot located on the southeast portion that was monitored from 2000 to 2013 and again since 2016 (Macey and Collins 2022). Prior to our study (2003–2016), pairing success was > 70%, fledging success ranged from 40 to 73%, and the return rates of banded males ranged from 23 to 60% across plots (Macey and Collins 2022). At CB, plots included: an 884-ha plot located at the northwest corner of CB, a 730-ha plot located on the west side of CB, and a 1008-ha plot located at the southwest corner of CB. Prior to our study (2015–2017), pairing success was > 80%, fledging success ranged from 33 to 81%, and the return rates of banded males ranged from 25 to 53% across plots (Finn et al. 2019).

Field methods

Beginning in early March (2017–2021 at FC and 2017–2019 at CB), we searched each plot from sunrise to ~1300 for Golden-cheeked Warblers that returned to the breeding grounds. We also searched for Golden-cheeked Warblers within a 200-m buffer around each plot because previously collected data indicated that 96% of returning birds that we relocated established their territory within 200 m of the territory they established the year prior (J. Macey, *personal observation*). We conducted these searches 1–5 times per week until the end of the breeding season (late June–early July) and we searched each plot a similar number of days. We also spent a similar amount of time searching for Golden-cheeked Warblers with and without geolocators (see below) because our goal was to compare responses between the groups.

When we detected a Golden-cheeked Warbler by sight or sound, we used a GPS unit to record the bird's latitudinal and longitudinal coordinates, and we noted the individual's sex, and the color combination of any bands present on their legs. After behavioral observations indicated that Golden-cheeked Warblers had established their territories, and, thus, were unlikely to move long distances from our plots (mid-to-late March), we captured individuals using standard mist-netting techniques with playback of conspecific songs (NABC 2001). We banded Golden-cheeked Warblers with a U.S. Geological Survey (USGS) aluminum leg band and two to three plastic color leg bands. For each bird, we recorded the USGS band number, color combination, date, and time; body mass to the nearest 0.01 g, sex, and age; and coordinates of all banding locations. We aged individuals as hatch year (HY), second year (SY), or after second year (ASY), and sexed each bird according to Pyle (1997) and Peak and Lusk (2009, 2011). Handling time for banded birds was typically < 5 min.

From 2017 to 2020, we used a modified version of a leg-loop harness (Rappole and Tipton 1991, Streby et al. 2015) to attach geolocators (Migrate Technology Intigeo P30Z11-7 Dip with a 5-mm light stalk; total weight 0.41 g with 0.5 mm stretch cord harness) to approximately half of the male Golden-cheeked Warblers we captured in each plot (Fig. 1). We deployed geolocators on individuals that weighed ≥ 9.2 g so that the weight of all attachments (i.e., USGS band, color bands, and geolocator with leg-loop harness) did not exceed 5.5% of the bird's body mass. Handling time for birds with geolocators was typically < 10 min. As stipulated by our permits, we did not deploy geolocators on females or re-deploy geolocators on males that we tagged in a previous year. From 2018 to 2021, we recaptured Golden-cheeked Warblers with geolocators (Fig. 1) to recover the devices and retrieve the stored data. For recaptures, we used the same mist-netting and data collection techniques described above, but additionally recorded observations of body condition (e.g., mass, feather abrasions, injuries).

Fig. 1. Left: Miniturized light-level geolocator (Migrate Technology Intigeo P30Z11-7 Dip with a 5-mm light stalk) and leg-loop harness (0.41 g). Center: Geolocator attached to male Golden-cheeked Warbler (*Setophaga chrysoparia*). Right: Geolocator retrieved from a male Golden-cheeked Warbler the year after it was attached. We conducted our study from 2017 to 2021 at Fort Cavazos and Joint Base San Antonio-Camp Bullis in Texas.

We observed all birds for up to 30 min after processing. If a released bird exhibited any flight or balance issues before they resumed normal activities (e.g., singing, foraging, territory defense, mate guarding), we noted the specific abnormal behaviors and later recorded post-release behavior as "1." If a released bird immediately flew off and resumed normal activities, we noted our observations and later recorded post-release behavior as "0."

From 2017 to 2021, we mapped and monitored Golden-cheeked Warblers with and without geolocators in each plot 1–5 times per week for the duration of the breeding season; individuals in each plot were monitored for a similar number of days across the breeding season. When we located a male Golden-cheeked Warbler, we used a handheld GPS unit to record the male's location every three (FC) or two (CB) min (≤ 2 hrs per visit at FC and ≤ 1 hr per visit at CB) or until the bird was no longer visible. We used the location data to define the boundaries of each male's territory (i.e., male relocated in the same area for > 2 weeks with > 20 location points) and to assist with relocation efforts during the current and subsequent breeding seasons. Differences in survey effort and the timing of GPS points recorded at FC and CB during territory monitoring visits reflected differences in concurrent research objectives and permit authorizations.

While mapping each territory, we recorded behavioral observations of each male to determine the individual's reproductive status. We defined individual pairing success as the presence of a female within the focal male's territory for > 2 weeks. We based fledging success on our observations at the nest site (e.g., male attended a nest and nest fledged at least one young) or our observations of a male feeding a fledgling. We may have missed some nestlings that fledged, but assume this happened infrequently given estimated daily survival rate of Golden-cheeked Warbler fledglings during the first four weeks post-fledging (i.e., 0.985 [95% CI = 0.971–0.993]; Trumbo et al. 2021), average movements of Golden-cheeked Warbler fledglings between daily observations (i.e., 44.20 ± 2.61 m; Trumbo et al. 2021), and the frequency of our visits to each territory (i.e., at least once per week). We conducted all field activities in accordance with the following permits: USFWS #TE023643-11, #TE32917C-1, and #TE082496-0; USGS #21999 and #24126; TPWD #SPR-0409-079, #SPR-0417-097; and Louisiana State University Animal Care and Use Protocols #2018-11 and #A2021-10.

Analyses

We used program R (V. 4.3.1; R Core Team 2023) with packages ggplot2 (V. 3.4.2; Wickham 2016) and emmeans (V. 1.8.7; Lenth 2023) to analyze our data and exported figures using ggpubr (V. 0.6.0; Kassambara 2023). First, we summarized the number of birds with and without geolocators that paired, fledged, or returned by study site, year, and age at first capture. We then fit generalized linear models with binomial distributions and logit link functions to examine the effects of geolocators, age, and year on pairing success, fledging success of birds that successfully paired, and return rate (Nelder and Wedderburn 1972). Each model included the interaction between age and geolocator and the additive effect of year. We did not include site in our models because sampling effort (i.e., number of years, size of plots, frequency and duration of territory visits) was different at FC and CB. We fit a model with the additive effects of age, geolocator, and year for pairing success at Fort Cavazos because the model including the interaction term did not converge.

We reported parameter estimates and 95% confidence intervals for each model and considered parameters with 95% confidence intervals that included 0 not significant (Burnham and Anderson 2002). However, we also reported predicted values and 95% confidence intervals for all parameters included in our models. Next, we described our observations of Golden-cheeked Warbler behavior following attachment of the geolocators (i.e., observations of flight and balance). Last, we described our observations of body condition upon retrieval of the geolocators and used paired t-tests ($\alpha = 0.05$) with data separated by age class to identify potential differences in mean body mass when we deployed and retrieved geolocators (Zar 1999).

RESULTS

We monitored 88 male Golden-cheeked Warblers with geolocators (SY n = 49 [56%], ASY n = 39 [44%]) and 47 Golden-cheeked Warblers without geolocators (SY n = 21 [45%], ASY n = 26 [55%]) at FC (Table 1). At FC, overall pairing success was 83% for Golden-cheeked Warblers with geolocators and 87% for Golden-cheeked Warblers without geolocators; overall fledging success was 48% for Golden-cheeked Warblers with geolocators and 73% for Golden-cheeked Warblers without geolocators; and overall return rates were 38% for Golden-cheeked Warblers with geolocators and 23% for Golden-cheeked Warblers without geolocators (Table 1). We monitored 34 male Golden-cheeked Warblers (SY n = 13 [38%], ASY; n = 21 [62%]) with geolocators and 66 (SY n = 18 [27%], ASY n = 48 [73%]) without geolocators at CB (Table 1). At CB, overall pairing success was 77% for Golden-cheeked Warblers with geolocators and 89% for Golden-cheeked Warblers without geolocators; overall fledging success was 73% for Golden-cheeked Warblers with geolocators and 80% for Golden-cheeked Warblers without geolocators; and overall return rates were 27% for Golden-cheeked Warblers with geolocators and 58% for Golden-cheeked Warblers without geolocators (Table 1).

Modeling

Most parameters we considered in our pairing success, fledging success, and return rate models were not statistically significant (Table 2). However, the model for Golden-cheeked Warbler fledging success at FC had a 95% confidence interval that did not include 0 for the 2020 parameter (Table 2). Predicted mean fledging success was lower in 2017 for SY birds with geolocators compared to ASY birds without geolocators in 2020 (Fig. 2). Other confidence intervals for predicted mean fledging success overlapped between 2017 and 2020 (Fig. 2). At CB, the return rate model had a 95% confidence interval that did not include 0 for the age and geolocator interaction parameter (Table 2). All ASY geolocator and year combinations had overlapping confidence intervals for predicted probability of return (Fig. 2). During both years, the mean predicted probability of return for SY Golden-cheeked Warblers at CB was, on average, 11 times greater for birds without geolocators than birds with geolocators (Fig. 2). Mean predicted probability of return for ASY Golden-cheeked Warblers without geolocators during both years was, on average, 10 times greater than SY Golden-cheeked Warblers with geolocators in 2017 (Fig. 2).

Table 1. Percent of male Golden-cheeked Warblers (*Setophaga chrysoparia*) that paired, fledged, and returned by site, year, and age (SY = second year; ASY = after second year) at Fort Cavazos and Joint Base San Antonio-Camp Bullis (Camp Bullis) in Texas. We collected our data from 2017 to 2021.

Site	Year	Age	Geolocator	*n*	Paired	Fledged[†]	Returned
Fort Cavazos							
	2017	SY	Geo	10	90%	22%	40%
			No geo	3	67%	50%	0%
		ASY	Geo	14	86%	42%	64%
			No geo	7	100%	57%	14%
		All ages	Geo	24	88%	33%	54%
			No geo	10	90%	56%	10%
	2018	SY	Geo	7	86%	50%	43%
			No geo	2	100%	50%	0%
		ASY	Geo	12	92%	64%	25%
			No geo	7	100%	86%	29%
		All ages	Geo	19	90%	59%	32%
			No geo	9	100%	78%	22%
	2019	SY	Geo	20	70%	50%	25%
			No geo	7	71%	60%	0%
		ASY	Geo	8	88%	43%	38%
			No geo	4	100%	100%	75%
		All ages	Geo	28	75%	48%	29%
			No geo	11	82%	78%	27%
	2020	SY	Geo	12	83%	40%	42%
			No geo	9	67%	83%	33%
		ASY	Geo	5	80%	100%	20%
			No geo	8	100%	75%	25%
		All ages	Geo	17	82%	57%	35%
			No geo	17	82%	79%	29%
	2017-2020	SY	Geo	49	80%	41%	35%
			No geo	21	71%	67%	14%
		ASY	Geo	39	87%	56%	41%
			No geo	26	100%	77%	31%
		All ages	Geo	88	83%	48%	38%
			No geo	47	87%	73%	23%
Camp Bullis							
	2017	SY	Geo	5	80%	50%	20%
			No geo	9	78%	71%	56%
		ASY	Geo	12	75%	67%	33%
			No geo	38	90%	82%	50%
		All ages	Geo	17	77%	62%	29%
			No geo	47	87%	81%	51%
	2018	SY	Geo	8	75%	83%	0%
			No geo	9	89%	88%	89%
		ASY	Geo	9	78%	86%	44%
			No geo	10	100%	70%	60%
		All ages	Geo	17	77%	85%	24%
			No geo	19	95%	78%	74%
	2017-2018	SY	Geo	13	77%	70%	8%
			No geo	18	83%	80%	72%
		ASY	Geo	21	76%	75%	38%
			No geo	48	92%	80%	52%
		All ages	Geo	34	77%	73%	27%
			No geo	66	89%	80%	58%

[†] Percent fledged calculated out of number that paired.

Table 2. Parameter estimates and 95% confidence intervals for generalized linear models examining the effects of geolocators (No Geo = without geolocator; Geo = with geolocator), age (SY = second year; ASY = after second year), and year on Golden-cheeked Warbler (*Setophaga chrysoparia*) pairing success, fledging success, and return rate at Fort Cavazos and Joint Base San Antonio-Camp Bullis (Camp Bullis) in Texas. We collected our data from 2017 to 2021. Asterisks (*) denote parameters with 95% confidence intervals that did not include 0 and colons (:) denote interactions between variables.

Site	Response	Parameter	Estimate	2.5%	97.5%
Fort Cavazos	Pairing success	Age SY	-1.06	-2.26	0.01
		Geo	-0.26	-1.39	0.78
		Year 2018	0.49	-1.25	2.54
		Year 2019	-0.52	-1.95	0.77
		Year 2020	-0.30	-1.80	1.12
	Fledging success	Age SY	-0.70	-2.19	0.79
		Geo	-0.89	-2.13	0.25
		Year 2018	1.04	-0.08	2.21
		Year 2019	0.94	-0.15	2.08
		Year 2020*	1.23	0.09	2.44
		Age SY:Geo	-0.08	-1.83	1.66
	Return rate	Age SY	-0.99	-2.64	0.45
		Geo	0.48	-0.58	1.58
		Year 2018	-0.58	-1.70	0.48
		Year 2019	-0.47	-1.51	0.54
		Year 2020	-0.13	-1.18	0.92
		Age SY:Geo	0.73	-0.94	2.57
Camp Bullis	Pairing success	Age SY	-0.93	-2.59	0.81
		Geo	-1.35	-2.88	0.12
		Year 2018	0.51	-0.70	1.82
		Age SY:Geo	0.88	-1.46	3.23
	Fledging success	Age SY	-0.09	-1.53	1.56
		Geo	-0.34	-1.69	1.12
		Year 2018	0.40	-0.72	1.61
		Age SY:Geo	-0.23	-2.59	2.09
	Return rate	Age SY	0.73	-0.44	2.01
		Geo	-0.70	-1.82	0.37
		Year 2018	0.53	-0.42	1.52
		Age SY:Geo*	-2.85	-6.02	-0.59

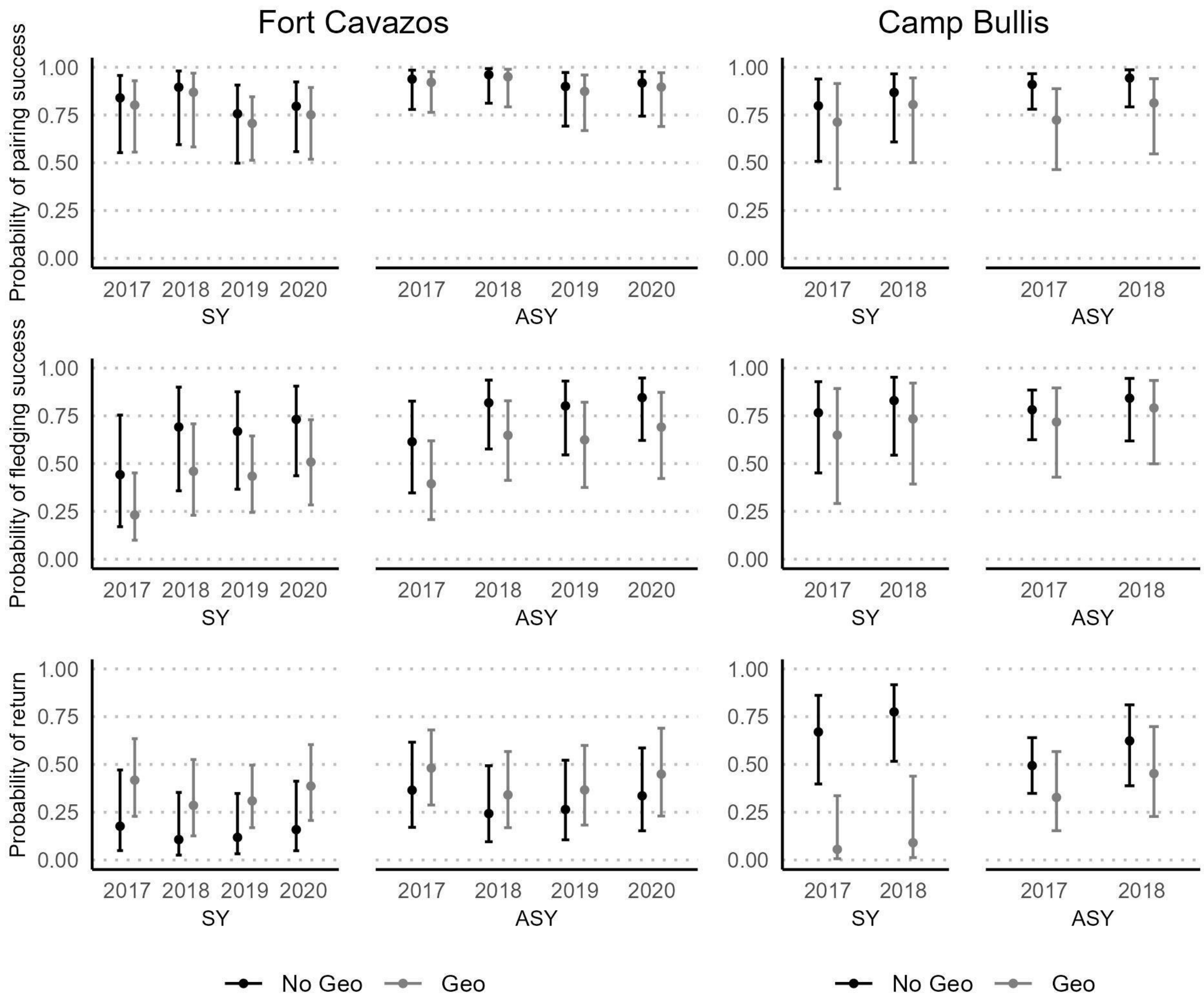
Behavior and body condition

Almost all Golden-cheeked Warblers quickly resumed normal activities (e.g., singing, foraging, territory defense, mate guarding) within 30 min after attaching the geolocators. We noted that 13 (11%; SY $n = 6$, ASY $n = 7$) out of 122 Golden-cheeked Warblers with geolocators were slow to fly off, had balance issues, or acted as if they were still captured upon initial release. However, these Golden-cheeked Warblers also resumed normal behavior within 30 min. Upon recapturing Golden-cheeked Warblers with geolocators, we documented minor feather abrasions under the geolocators and slight skin irritation under the legs from the harnesses in 7 out of 32 individuals (22%) across both study sites. We are unable to report masses at CB because of low sample sizes. However, we found no statistically significant difference between the mean mass of SY Golden-cheeked Warblers ($n = 15$) when we deployed (9.69 ± 0.32 g) and retrieved (9.70 ± 0.40 g) geolocators at FC ($t_{14} = 0.17$, $P = 0.87$). We also found no statistically significant difference between the mean mass of ASY Golden-cheeked Warblers ($n = 15$) when we deployed (9.76 ± 0.37 g) and retrieved (9.84 ± 0.49 g) geolocators at FC ($t_{14} = 0.61$, $P = 0.55$). We could not compare the mean mass difference between years of non-geolocator birds because we did not recapture non-geolocator birds in subsequent seasons. However, the mean mass for all banded SY Golden-cheeked warblers without geolocators at FC ($n = 52$) was 9.34 ± 0.43 g (range 8.40–10.17 g), and for the ASY group ($n = 20$) was 9.57 ± 0.59 g (range 8.70–11.00 g).

DISCUSSION

Overall, Golden-cheeked Warbler pairing success, fledging success, and return rates at FC and CB across age classes and years were consistent with previous estimates at each study site (Finn et al. 2019, Macey and Collins 2022), additional research at FC (Jetté et al. 1998, MacAllister et al. 2007, Duarte et al. 2014), and research conducted by others (reviewed by Groce et al. 2010). Regardless, we did find lower return rates for SY Golden-cheeked Warblers with geolocators compared to Golden-cheeked Warblers without geolocators in both age classes at CB. Our sample size for SY Golden-cheeked Warblers at CB was low and we did not find similar results at FC; although not statistically

Fig. 2. Predicted values and 95% confidence intervals for all model parameters in our generalized linear models examining the effects of geolocators (No Geo = without geolocator; Geo = with geolocator), age (SY = second year; ASY = after second year), and year on Golden-cheeked Warbler (*Setophaga chrysoparia*) pairing success, fledging success, and return rate at Fort Cavazos and rate at Joint Base San Antonio-Camp Bullis (Camp Bullis) in Texas. We collected our data from 2017 to 2021.



significant and contrary to our predictions, return rates at FC tended to be higher for Golden-cheeked Warblers with geolocators compared to Golden-cheeked Warblers without geolocators in both age classes. Further, it is possible that we did not detect Golden-cheeked Warblers in the SY age class with geolocators that returned or that these birds relocated beyond our search radius. However, Golden-cheeked Warblers have high return rates (Groce et al. 2010, Finn et al. 2019, Macey and Collins 2022), high site fidelity (Jetté et al. 1998, Mass-Burleigh 1998, Groce et al. 2010), and often return within 200 m of their previous year's territories (J. Macey, *personal observation*). In addition, we conducted frequent visits to each site and spent a similar amount of time searching for Golden-cheeked Warblers in each group. Although it is not uncommon for SY birds to return at lower rates than ASY birds (Jetté et al. 1998; J. Macey, *personal observation*), we believe the relative difference we found in return rates between SY Golden-cheeked Warblers with and without geolocators should encourage other researchers to consider the potential effects of geolocators on younger birds during future studies. Moreover, we urge others to report the results of geolocator studies by age class, even if sample sizes preclude age as a factor for analyses, which could help researchers design better studies and minimize potential bias in tracking data.

We acknowledge that, although not statistically significant, fledging success tended to be lower for Golden-cheeked Warblers with geolocators, and the inclusion of other metrics (e.g., nest success, nestling provisioning rates, nest timing) or the timing of observations may have yielded different results. Raybuck et al. (2017a) found no evidence that geolocators had a negative effect on nest survival and provisioning rates or within season survival of Cerulean Warblers and Bell et al. (2017) found that geolocators did not impact provisioning effort, nestling growth, or nest success of Pied Flycatchers (*Ficedula hypoleuca*). However, Arlt et al.

(2013) found carry-over effects wherein Northern Wheatears (*Oenanthe oenanthe*) with geolocators had lower nest success than those without geolocators during the subsequent breeding season. Despite the increasing popularity of geolocators as a tool to study the migration ecology of songbirds, there are still few papers that report the potential impacts of geolocators on aspects of reproductive behavior, especially for small songbirds < 12 g, and many geolocator impact studies have low sample sizes or represent individuals from a small portion of a species' breeding range. Species-specific studies suggest mixed responses and reiterate the need for continued research on this topic that includes a wide range of metrics.

Similar to others (Peterson et al. 2015, Raybuck et al. 2017a), we did not find a statistically significant difference between the mean mass of male Golden-cheeked Warblers when we deployed and retrieved geolocators at FC (CB excluded from analyses because of low sample sizes) or evidence of extensive skin abrasions or feather wear due to the geolocator harness. These results are encouraging with respect to migration research, but it is important to note that the mass of male Golden-cheeked Warblers ranges from 8 to 12 g and we deployed geolocators on individuals that weighed ≥ 9.2 g. As such, we may have attached geolocators to individuals in better overall body condition when they arrived at the breeding grounds. In addition, male Golden-cheeked Warblers with geolocators that returned to our study sites in subsequent seasons may have been in better body condition than male Golden-cheeked Warblers with geolocators that did not return. Also, the timing of the individual weights measured may have impacted our results. We recaptured most individuals at the beginning of the breeding season because individuals are more responsive to playback calls and are more susceptible to target netting during this period. If the geolocators influenced male Golden-cheeked Warbler weight during migration, it is possible that the individuals had sufficient time to regain weight prior to recapture.

There are other body condition measures we did not consider (e.g., fat scoring, abdominal profiles; Labocha and Hayes 2012), which may have provided further insight into the health of individuals at the time of capture. However, Labocha and Hayes (2012) suggest that mass alone may serve as a sufficient proxy for other body condition indices. We will add here that of the 13 (11%; SY $n = 6$, ASY $n = 7$) out of 122 male Golden-cheeked Warblers with geolocators that were slow to fly off, had balance issues, or acted as if they were still captured upon initial release following our attachment of the geolocators, only 2 (15%; SY $n = 1$, ASY $n = 1$) out of the 13 returned the following season. This could have been caused by the geolocator itself or by issues associated with capture, handling, or fit of the harness that we did not detect during deployment. Though decisions should be made on a case-by-case basis and further documentation is needed to confirm if these results are consistent across studies, researchers may want to consider recapturing individuals that exhibit these behaviors and check the harness fit or remove the geolocator for use on another bird.

Male Golden-cheeked Warblers were a good candidate for movement research using geolocators because they have high annual return rates (Groce et al. 2010, Macey and Collins 2022), strong site fidelity, (Jetté et al. 1998, Maas-Burleigh 1998), and high recapture rates on the breeding grounds (J. Macey, *personal observation*). In addition, the male Golden-cheeked Warblers at our study sites were monitored consistently across the breeding season. Thus, we were able to obtain relatively large sample sizes across multiple study sites and years for our project, allowing us to broadly examine geolocator effects for the species. However, the migration ecology of female Golden-cheeked Warblers, and females of most species, is still virtually unknown. Geolocator data could help us close this gap, but we encourage more studies that explore the potential impacts of geolocators on females because they may respond differently than males. For example, geolocators could hinder copulation or females with tags may be more prone to entanglement issues if females spend more time in dense vegetation while foraging or gathering nest material than their male counterparts.

CONCLUSION

North American bird populations have experienced steep declines in recent decades, with an estimated net loss approaching 3 billion birds (Rosenberg et al. 2019). These net losses include an estimated 2.5 billion native migratory birds representing 419 species (Rosenberg et al. 2019). Migration data that helps us identify breeding and non-breeding habitats in need of protection and enact conservation agreements, initiatives, or memoranda of understanding for species that cross jurisdictional boundaries (e.g., Partners in Flight, Working Lands for Wildlife, Americas Flyways Initiative, Migratory Birds Joint Venture, Convention on the Conservation of Migratory Species of Wild Animals) are critical to reverse these population declines. However, migration data must be collected in such a way that minimizes potential harm to birds. We hope our study encourages continued research that explores the potential impacts of geolocators on other species. Such information is necessary to assist governing bodies with permitting decisions, guide and promote the safe and ethical use of tracking devices by researchers (Geldart et al. 2022), and minimize potential biases in tracking data (Jewell 2013).

Author Contributions:

JNM and AML obtained funding; JNM and AML wrote the manuscript with contributions from KRC, MDG, NG, NMR, JMK, DF, MRC, and SC; JNM, JMK, and AML conducted the analysis; JNM, KRC, MDG, NG, NMR, DF, MRC, SC, and AML conducted field research.

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Data Availability:

Upon request.

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