THE CONDOR
Ornithological Applications
AmericanOrnithology.org

Volume 117, 2015, pp. 249–255
DOI: 10.1650/CONDOR-14-182.1

RESEARCH ARTICLE

Minimizing marker mass and handling time when attaching radio-transmitters and geolocators to small songbirds

Henry M. Streby,[1]* Tara L. McAllister,[2] Sean M. Peterson,[2] Gunnar R. Kramer,[2] Justin A. Lehman,[2,a] and David E. Andersen[3]

[1] Department of Environmental Science Policy and Management, University of California, Berkeley, California, USA
[2] Minnesota Cooperative Fish and Wildlife Research Unit, Department of Fisheries, Wildlife, and Conservation Biology, University of Minnesota, St. Paul, Minnesota, USA
[3] U.S. Geological Survey, Minnesota Cooperative Fish and Wildlife Research Unit, St. Paul, Minnesota, USA
[a] Current address: Department of Forestry, Wildlife, and Fisheries, University of Tennessee, Knoxville, Tennessee, USA
* Corresponding author: henrystreby@gmail.com

Submitted November 15, 2014; Accepted February 15, 2015; Published April 29, 2015

ABSTRACT

Radio-transmitters and light-level geolocators are currently small enough for use on songbirds weighing <15 g. Various methods are used to attach these markers to larger songbirds, but with small birds it becomes especially important to minimize marker mass and bird handling time. Here, we offer modifications to harness materials and marker preparation for transmitters and geolocators, and we describe deployment methods that can be safely completed in 20–60 s per bird. We describe a 0.5-mm elastic sewing thread harness for radio-transmitters that allows nestlings, fledglings, and adults to be marked with the same harness size and reliably falls off to avoid poststudy effects. We also describe a 0.5-mm jewelry cord harness for geolocators that provides a firm fit for >1 yr. Neither harness type requires plastic or metal tubes, rings, or other attachment fixtures on the marker, nor do they require crimping beads, epoxy, scissors, or tying knots while handling birds. Both harnesses add 0.03 g to the mass of markers for small wood-warblers (Parulidae). This minimal additional mass is offset by trimming transmitter antennas or geolocator connection nodes, resulting in no net mass gain for transmitters and 0.02 g added for geolocators compared with conventional harness methods that add >0.40 g. We and others have used this transmitter attachment method with several small songbird species, with no effects on adult and fledgling behavior and survival. We have used this geolocator attachment method on 9-g wood-warblers with no effects on return rates, return dates, territory fidelity, and body mass. We hope that these improvements to the design and deployment of the leg-loop harness method will enable the safe and successful use of these markers, and eventually GPS and other tags, on similarly small songbirds.

Keywords: attachment methods, geolocation, migration, telemetry, warbler, wildlife tracking

Minimizando el peso de los marcadores y el tiempo de manipulación al colocar radio transmisores y geo-localizadores a aves canoras pequeñas

RESUMEN

Los radio transmisores y los geo-localizadores con detectores de nivel de luz son actualmente lo suficientemente pequeños como para ser usados en aves canoras <15 g. Se usan varios métodos para fijar estos marcadores a aves más grandes, pero con aves canoras pequeñas es particularmente importante minimizar el peso de los marcadores y el tiempo de manipulación. En este trabajo, proponemos una serie de modificaciones a los materiales del arnés y a la preparación de los marcadores para los transmisores y los geo-localizadores, y describimos métodos de fijación que pueden implementarse de modo seguro en 20 a 60 segundos por ave. Describimos un arnés de hilo de coser elástico de 0.5 mm para radio transmisores que permite marcar pichones, volantones y adultos con el mismo tamaño de arnés, y que se desprende de modo fiable para evitar efectos posteriores al estudio. Adicionalmente, describimos un arnés de cordón de joyería de 0.5 mm para los geo-localizadores que brinda un ajuste firme por >1 año. Ninguno de los tipos de arnés requiere tubos de plástico o metal, anillos u otros accesorios de fijación en el marcador, ni tampoco requieren engarzado de cuentas, pegamentos, tijeras o ataduras mientras se manipula a las aves durante la colocación. Ambos arneses agregan 0.03 g de peso a los marcadores para las pequeñas aves Parulidae. Este aumento mínimo del peso es compensado por el recorte de las antenas de los transmisores o de los nodos de conexión de los geo-localizadores, lo que conlleva a un aumento nulo del peso de los transmisores y a un aumento de 0.02-g para los geo-localizadores, en comparación con los arneses convencionales que agregan >0.40 g. Nosotros y otras personas han usado este método de fijación con muchas especies de aves canoras pequeñas, sin efectos en el comportamiento ni en la supervivencia de los adultos y de los pichones. Hemos usado este método de fijación del geo-localizador en Parúlidos de bosque de 9 g sin efectos en las tasas de retorno, las fechas de retorno, la fidelidad territorial y el peso corporal. Esperamos que estas mejoras al diseño y al método de colocación del arnés de las perneras permitan un uso seguro y exitoso de estos marcadores, y eventualmente de GPS u otras marcas en aves pequeñas del mismo tipo.

Palabras clave: geo-localización, métodos de fijación, migración, Parulidae, rastreo de vida silvestre, telemetría

INTRODUCTION

The knowledge that can be gained from marking songbirds with radio-transmitters (hereafter, transmitters) and data loggers such as light-level geolocators (hereafter, geolocators) is immense (e.g., Anders et al. 1998, Stutchbury et al. 2009, Delmore et al. 2012, Streby et al. 2014). Miniaturization of these markers has progressed to allow birds <15 g to be marked (Streby et al. 2012, Salewski et al. 2013, Zenzal et al. 2014). A basic assumption of studies involving marking animals is that the application of markers and the carrying of those markers by individuals do not affect their behavior or survival (White and Garrott 1990). Therefore, when marking very small animals, key objectives are to minimize the mass of the marker and the time spent handling an animal when applying the marker. The leg-loop figure-eight harness design described by Rappole and Tipton (1991) is used in most radio-telemetry and light-level geolocation studies of songbirds (Bridge et al. 2013, Cox et al. 2014). However, there is substantial variation in the interpretation and application of that design, although authors generally report the method as the leg-loop or figure-eight harness design, and cite Rappole and Tipton (1991).

Although the details of author-specific harness designs and attachment methods are rarely described in the peer-reviewed literature, many are readily accessible online, and these methods usually involve considerably more and heavier materials and far greater handling time than described by Rappole and Tipton (1991). For example, harness materials ranging from embroidery thread to Teflon ribbon are attached to markers prefabricated with metal and plastic tubes and rings intended to facilitate the attachment of harnesses to transmitters and geolocators. In addition, although Rappole and Tipton (1991) described a fully prepared harness applied with minimal handling time in the field, incomplete harnesses are often fitted to birds using scissors, crimping beads, the tying of knots, and application of epoxy, requiring extensive handling time. Some heavy and strong materials, paired with complicated attachment procedures, may be necessary for marking larger birds that might destroy lighter harnesses, or for species with great individual size variation. However, those materials and methods are not necessary for marking small songbirds, and their presumed necessity likely contributes to the opinion that very small species, such as many wood-warblers (Parulidae), cannot be safely marked with transmitters or similar markers (Confer et al. 2011).

Caution in marking very small songbirds is justified, considering the apparent underreporting of negative transmitter effects on songbirds (Hill and Elphick 2011), the relatively low return rates, compared with controls, of 12-g birds marked with geolocators (Salewski et al. 2013), and the paucity of controlled comparisons in transmitter and geolocator studies in general (but see Townsend et al. 2012, Bridge et al. 2013). However, instead of waiting for transmitters and geolocators to become small enough to accommodate the mass of conventional harness designs, here we demonstrate that considerable progress can be made in minimizing the mass of the harness itself (Table 1). We suggest a return to the simplicity of Rappole and Tipton's (1991) original design, and we offer modifications to minimize harness mass and deployment time. We developed and tested this method with controlled comparisons for both transmitters and geolocators, with no measurable effects on birds as small as 9 g.

METHODS

Radio-Transmitters

We used the leg-loop harness design (Rappole and Tipton 1991), with the modifications described below, to deploy radio-transmitters on >500 adult, nestling, and fledgling Ovenbirds (*Seiurus aurocapilla*; 13 g at fledging, 19 g as adults) and Golden-winged Warblers (*Vermivora chrysoptera*; 7 g at fledging, 9 g as adults), with no effects, compared with banded control birds, on behavior, reproductive success, and survival (Streby and Andersen 2013, Streby et al. 2013). We have instructed others in this method who have used it to mark Japanese White-eyes (*Zosterops japonicus*; 10 g; Wu et al. 2014), Acadian Flycatchers (*Empidonax virescens*; 13g; J. Jenkins personal communication), and Golden-winged Warblers (J. Lehman and D. McNeil personal communication), with no apparent effects on behavior or survival (i.e. no observations of obvious behavioral changes or limitations, or of obvious transmitter-caused mortality). Additionally, we and others have used this method to radio-tag larger songbirds, including Bachman's Sparrows (*Peucaea aestivalis*; 21 g; A. Fish personal communication), Hermit Thrushes (*Catharus guttatus*; 30 g), Wood Thrushes (*Hylocichla mustelina*; 50 g), and Omao (or ʻŌmaʻo; *Myadestes obscurus*; 50 g; Wu et al. 2014), with no indication that heavier harness materials or more complicated deployment methods are necessary to avoid harness failure in these species.

TABLE 1. Masses (g) of materials used to deploy a geolocator on a small songbird using a common conventional method and our modifications.

	Manufactured parts				Added parts			
Method	Base geolocator [a]	Anterior tube	Posterior rings & nodes [b]	Light stalk	Crimping beads	Harness	Total, deployed unit	Mass limit of bird [c]
Conventional	0.43	0.10	0.10	≥0.05	≥0.06	≥0.12	≥0.89	≥17.8
Modified	0.43	0.00	−0.01	0.00	0.00	0.03	0.45	9.0

[a] Biotrack model ML6340 (Biotrack, Wareham, Dorset, UK), guaranteed for 9 mo, but 87% collected data for >12 mo in our study.
[b] Metal rings that normally double as points of electrical connection and harness connection are unnecessary with our modified method, and we trim 0.01 g off the simple electrical nodes.
[c] Minimum mass of birds that can be marked, assuming that the marker is ≤5% of body mass.

Our modifications to Rappole and Tipton's (1991) transmitter harness design include harness material, construction, and attachment to the transmitter. Rappole and Tipton (1991) described using catheter tubing or other ligature materials ≥1 mm in diameter to avoid skin abrasion. We used a very thin (~0.5 mm) black elastic sewing thread (Gutermann Thread, Gutach-Breisgau, Germany; available online and at most craft stores) and observed no skin irritation around the legs of birds that wore the harness >50 days. We speculate that this lack of abrasion is due to each loop of this harness being a true loop that fits snugly around the thigh against the body and does not slide forward and backward as harnesses attached to the front and back of a marker may do. Thin elastic sewing thread offers multiple benefits in addition to having considerably less mass than thicker, more rigid materials. First, the elasticity allows for ease of attachment when stretching around a bird's leg. Second, the elasticity allows for a one-size-fits-all approach within species lacking substantial individual size variation, and harnesses sized for adults fit securely on nestlings and fledglings as they grow. Finally, thin elastic thread degrades and allows the harness to fall off the bird 40–70 days after deployment. This is important because small songbirds that migrate with radio-transmitters attached with thicker, longer-lasting harness materials can experience reduced return rates (Chandler 2010). A weak link of rubber band or other soft material can be used if shorter monitoring periods are necessary for retrieving unexpired transmitters or when data are collected for brief periods. However, fledgling Ovenbirds, for which our transmitters lasted >50 days, started shedding harnesses with no weak link after 40 days. In addition, adult female Golden-winged Warblers that we marked before the nesting season lost their harnesses during the postfledging period, when we observed them feeding radio-tagged fledglings 50–70 days after female marking.

Preparation of the figure-eight harness is as simple as tying your shoes (Figure 1). We recommend determining appropriate harness size with field trials on a small sample of your focal species if the species has not been marked before. Formulas for estimating harness size based on body mass have been published with the intent of reducing this time and effort in the field (e.g., Naef-Daenzer 2007). However, although such formulas might produce a valuable starting point for field trials, the Naef-Daenzer (2007) formula overestimated harness size and produced harnesses that fell off Golden-winged Warblers (75% fell off), Ovenbirds (100%), and Hermit Thrushes (100%) within 24 hr of deployment during our initial trials (H. Streby personal observation).

Attachment of the harness to the transmitter requires only two tiny beads of superglue (Figure 1; we use Loctite Gel Control; Henkel Corporation, Rocky Hill, Connecticut, USA). This method minimizes the mass of the transmitter unit by removing the need for prefabricated plastic or metal rings or tubes for attaching or tying the harness to the transmitter. We have never had a transmitter ($n > 500$) come loose from the harness with this method. If transmitter antennas are trimmed to 6–7 cm (recommended to avoid tangling in vegetation), the 0.03-g mass of this harness can be entirely offset. This method also minimizes handling time of individuals or broods by having transmitters prepared for deployment before capturing birds or removing broods from nests. We prepared harnesses and attached them to transmitters >12 hr before deployment. Methods that involve fitting, tying, crimping, cutting, and gluing harnesses during bird handling often require >5 min per bird of unnecessary handling time and increased risk of injury from scissors and crimping pliers. Our method is also faster than glue-on methods that require drying time, which varies by glue type and environmental conditions. Using our method, a transmitter can be safely attached to a small songbird by an experienced handler in ~20 s.

We attach the transmitter to the bird in the same fashion as Rappole and Tipton (1991), but we offer minor clarifications here. Rappole and Tipton (1991) describe pulling the harness loops up to the proximal ends of the thighs, but their figure 1 does not include the thigh and

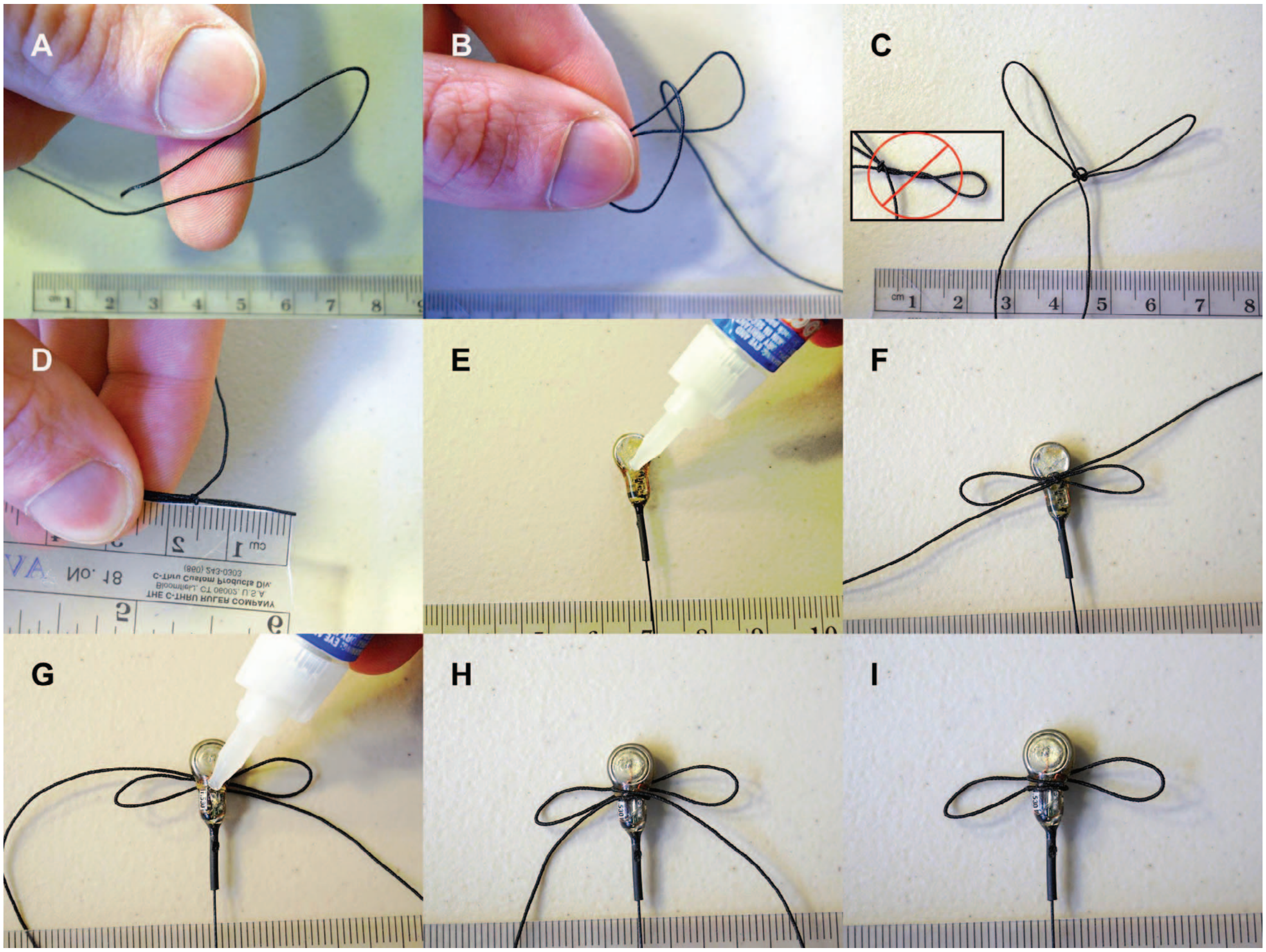

FIGURE 1. Building a harness and applying it to a radio-transmitter. The 0.5-mm elastic sewing thread is first cut into a segment of $\geq$10 cm. Then (**A**) one end of the thread is made into one loop, (**B**) the remaining long end is wrapped around the first loop, and (**C**) the long end is pulled through, resulting in a second loop and resembling bunny ears, with no twisting in the loops (**C**, inset). The knot is then tightened and, (**D**) using a thin ruler, the loops are adjusted to the desired inner-loop length when pulled taut but not stretched. The harness is attached to the transmitter by (**E**) placing a small bead of glue on the bottom of the unit at the base of the battery, roughly at the balancing point of the transmitter. Next, (**F**) the knot of the harness is held on the bead of glue with the harness loops held perpendicular to the transmitter while the glue dries (a few seconds). Then (**G**) the transmitter is rolled over and another bead of glue is applied in the same position on the top of the unit. Finally, (**H**) the long tails of the harness are pulled snugly around the transmitter and held in that second bead of glue until it dries, and (**I**) the long tails are clipped flush with the transmitter. For geolocators the method is identical, except that the sewing elastic is replaced by 0.5-mm Stretch Magic jewelry cord (Pepperell Braiding Company, Pepperell, Massachusetts, USA), and a bead of glue may be required to hold the knot made in step C due to the less agreeable material. For large numbers of markers, an assembly line approach is recommended for efficiency. A detailed presentation of this harness-making method and a video of geolocator deployment are available on the Minnesota Cooperative Fish and Wildlife Research Unit website (http://mncoopunit.cfans.umn.edu/published-methods-and-data/methods/) or by contacting the corresponding author.

depicts a loose-fitting harness loop riding somewhere distal to the knee. In our method, the loop should fit snugly against the body at the proximal end of the thigh. This fitting should be double-checked before release; if the harness loop is loose or distal to the knee the transmitter will fall off shortly after deployment (H. Streby personal observation). Rappole and Tipton (1991) also describe the transmitter sitting on the back of the bird with 1–2 mm of play. An additional benefit of the elastic harness is that it fits snugly against the bird, reducing the probability of skin abrasion from marker movement and reducing the chance of vegetation tangling under the harness. The transmitter can be fitted below the feathers for concealment or atop the feathers for less feather displacement, but either way it should fit snugly enough to not move, but should not be so snug that it affects behavior (i.e. the ability to perch correctly).

Geolocators

Our geolocator harness design is identical to the design that we use for transmitters, but is constructed of a different harness material. For geolocator harnesses we use 0.5-mm black Stretch Magic jewelry cord (Pepperell Braiding Company, Pepperell, Massachusetts, USA). Again, Rappole and Tipton (1991) called for materials $\geq$1 mm in diameter, and thicker versions of this jewelry cord have been used in geolocator studies (e.g., Ross et al. 2014). However, doubling the diameter of a round material quadruples its mass, so 1-mm cord would add 0.09 g of unnecessary mass (a 20% increase in total marker mass) to our Golden-winged Warbler marker. Although the jewelry cord and elastic thread that we use are similar in diameter, the jewelry cord has $\sim$10% of the elasticity of the sewing thread and shows no sign of degradation 1 yr after deployment on birds (Peterson et al. 2015). As with transmitters, we attach the harness to the geolocator >12 hr before deployment with two tiny beads of superglue and with no prefabricated tubes, rings, or other attachment points on the geolocator. We have not had a geolocator (n = 40) come loose from the harness with this method. For Golden-winged Warblers, the attached harness adds 0.03 g to the geolocator. We partially offset that mass by clipping $\sim$1 mm from each of the nodes used to connect the geolocator to a computer (this does not affect the ability to download data).

To attach a geolocator to a small songbird we again follow Rappole and Tipton's (1991) attachment methods, with further modifications due to the limited elasticity of the harness material. The two key modifications include an additional step to work the less-flexible material into place and a convenient method for ensuring that the geolocator rests atop the feathers to reduce potential feather obstruction of the light sensor. We first slide the right harness loop over the right foot to the tibiotarsal joint (as opposed to pulling the loop above the knee as with a transmitter harness). We then place a long, thin strip of paper or plastic on the bird's back, from the neck to the tail, covering the synsacrum where the geolocator will rest. After placing this strip, we pull the geolocator across the bird's back and slide the left harness loop over the outside of the closed left tibiotarsal joint. This method exploits the natural flexibility of passerine legs, so to perform it correctly we do not secure the right leg while we pull the left loop over the left tibiotarsal joint, but instead allow the right leg to move naturally behind the bird. This flexibility is similar to moving your elbows behind your back. We then pull the left harness loop up the left foot and over the toes, resulting in the geolocator resting on top of the strip with both loops inside the tibiotarsal joints. From this point we work both loops above the knees to rest snugly against the body, just as with the transmitter harness. Extending the human elbow analogy, this harness attachment method is similar to putting backpack straps on one elbow at a time behind your back, and then shrugging the pack into place on your shoulders. After securing the geolocator harness on both legs, we pull the strip out from under the harness toward the tail, thereby smoothing all feathers underneath the harness. If some feathers are left out of place, we pull the paper through again in the same direction to flatten those feathers under the geolocator and harness. Using this method, we have found that light stalks are not necessary to keep geolocator sensors above the feathers of small songbirds (Peterson et al. 2015). Interestingly, Golden-winged Warblers returning with geolocators tended not to have feathers over the geolocator, despite a year of molting and preening (H. Streby personal observation).

Similarly to the transmitter attachment method, this geolocator attachment method requires substantially less handling time than fitting incomplete harnesses in the field. Using our method, an experienced handler can independently attach a geolocator to a small songbird in <1 min. We used this method on adult male Golden-winged Warblers in 2013–2014 and observed a 46% return rate for geo-tagged birds, compared with 44% for control birds (Peterson et al. 2015). Only 1 of 40 marked Golden-winged Warblers returned without its geolocator or harness; this bird was one of the first that we marked when still working out the harness loop size (Peterson et al. 2015). Unlike our results with transmitters, we observed a small area ($\sim$3 $\times$ 3 mm) of callused skin under the geolocator on many Golden-winged Warblers. This featherless area was not directly associated with the harness and was more common on birds carrying geolocators with light stalks, which might have been due to the greater mass of those units or might have indicated that those units moved around more, presumably from wind drag and bumping the stalk on vegetation. However, because stalks are not necessary to keep light sensors above the feathers of Golden-winged Warblers (Peterson et al. 2015), and likely other small songbirds, we do not anticipate this abrasion being a problem in future studies using this method.

RESULTS

Our method for minimizing the mass of markers and the handling time required to deploy them on small songbirds has proven successful with the species marked so far. However, we caution that pilot studies with marked and control groups of moderate numbers of individuals remain important for new studies because marker effects on birds tend to be species- and study-specific (Sykes et al. 1990, Hill et al. 1999, Dougill et al. 2000, Mattsson et al. 2006, Hill and Elphick 2011). In addition, we caution that adult songbirds can take several minutes to acclimate to a new marker and should therefore be released in a reasonable location (i.e. not into wet vegetation or near a flock of corvids) and should be monitored closely until regular behavior is resumed. This acclimation period, which can entail short, awkward flights and sometimes pecking at new markers with the bill, has been more pronounced in males than in females in our experience, possibly due to females being more accustomed to sudden changes in mass distribution (i.e. laying eggs). We have observed no differences in behavior between radio-tagged nestlings and their unmarked broodmates in the nest or after fledging, presumably due to acclimation occurring before fledging or flying.

DISCUSSION

As the development of progressively smaller and longer-lasting radio-transmitters, geolocators, and other data loggers continues, efforts to mark progressively smaller songbirds will follow. However, improvements to harness designs and attachment techniques can make current markers available for use on many species that are too small for marking with conventional methods. Compared with conventional harness designs, our modifications to the leg-loop harness mean that >80 additional Neotropical migrant songbirds, including 62% of wood-warblers, can be marked with geolocators, radio-transmitters, and other markers, with geolocators already available (assuming the arbitrary 5% body mass rule; mass data from Poole [2005]). We hope that improvements to these methods, as well as results showing the effects of markers, will become more common in the peer-reviewed literature. Finally, our method is intended to improve upon methods developed by Rappole and Tipton (1991), and we therefore recommend that any citation of this work be in addition to, and not in place of, citation of their work.

ACKNOWLEDGMENTS

We thank N. Seavy and R. Cormier for discussion on geolocator harness design and materials. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government or other author affiliations.

Funding statement. These methods were developed during projects funded by the U.S. Fish and Wildlife Service and U.S. Geological Survey (USGS) through Research Work Order Nos. 73, 87, and 98 at the USGS Minnesota Cooperative Fish and Wildlife Research Unit; by the National Science Foundation through Postdoctoral Research Fellowship No. 1202729 to H.M.S.; and by the U.S. Department of Agriculture Natural Resources Conservation Service in a grant administered by Indiana University of Pennsylvania. None of the funding agencies influenced the content of this manuscript.

Ethics statement. We captured, marked, and collected data from songbirds following Protocol Nos. 0806A35761 and 1004A80575 approved by the University of Minnesota Institutional Animal Care and Use Committee (IACUC) and Protocol No. 561 approved by the University of Tennessee IACUC.

LITERATURE CITED

Anders, A. D., J. Faaborg, and F. R. Thompson, III (1998). Postfledging dispersal, habitat use, and home-range size of juvenile Wood Thrushes. The Auk 115:349–358.

Bridge, E. S., J. F. Kelly, A. Contina, R. M. Gabrielson, R. B. MacCurdy, and D. W. Winkler (2013). Advances in tracking small migratory birds: A technical review of light-level geolocation. Journal of Field Ornithology 84:121–137.

Chandler, R. B. (2010). Avian ecology and conservation in tropical agricultural landscapes with emphasis on *Vermivora chrysoptera*. Ph.D. dissertation, University of Massachusetts, Amherst, MA, USA.

Confer, J. L., P. Hartman, and A. Roth (2011). Golden-winged Warbler (*Vermivora chrysoptera*). In The Birds of North America Online (A. Poole, Editor), Cornell Lab of Ornithology, Ithaca, NY, USA. http://bna.birds.cornell.edu/bna/species/020. doi:10.2173/bna.20

Cox, W. A., F. R. Thompson, III, A. S. Cox, and J. Faaborg (2014). Post-fledging survival in passerine birds and the value of post-fledging studies to conservation. Journal of Wildlife Management 78:183–193.

Delmore, K. E., J. W. Fox, and D. E. Irwin (2012). Dramatic intraspecific differences in migratory routes, stopover sites and wintering areas, revealed using light-level geolocators. Proceedings of the Royal Society of London, Series B 279: 4582–4589.

Dougill, S. J., L. Johnson, P. C. Banko, D. M. Goltz, M. R. Wiley, and J. D. Semones (2000). Consequences of antenna design in telemetry studies of small passerines. Journal of Field Ornithology 71:385–388.

Hill, I. F., B. H. Cresswell, and R. E. Kenward (1999). Field testing the suitability of a new back-pack harness for radio-tagging passerines. Journal of Avian Biology 30:135–142.

Hill, J. M., and C. S. Elphick (2011). Are grassland passerines especially susceptible to negative transmitter impacts? Wildlife Society Bulletin 35:362–367.

Mattsson, B. J., J. M. Meyers, and R. J. Cooper (2006). Detrimental impacts of radiotransmitters on juvenile Louisiana Waterthrushes. Journal of Field Ornithology 77:173–177.

Naef-Daenzer, B. (2007). An allometric function to fit leg-loop harnesses to terrestrial birds. Journal of Avian Biology 38: 404–407.

Peterson, S. M., H. M. Streby, G. R. Kramer, J. A. Lehman, D. A. Buehler, and D. E. Andersen (2015). Geolocators on Golden-winged Warblers do not affect migratory ecology. The Condor: Ornithological Applications 117:256–261.

Poole, A. (Editor) (2005). The Birds of North America Online. Cornell Lab of Ornithology, Ithaca, NY, USA. http://bna.birds.cornell.edu/bna/

Rappole, J. H., and A. R. Tipton (1991). New harness design for attachment of radio transmitters to small passerines. Journal of Field Ornithology 62:335–337.

Ross, J. D., E. S. Bridge, M. J. Rozmarynowycz, and V. P. Bringman (2014). Individual variation in migratory path and behavior among Eastern Lark Sparrows. Animal Migration 2:29–33.

Salewski, V., M. Flade, A. Poluda, G. Kiljan, F. Liechti, S. Lisovski, and S. Hahn (2013). An unknown migration route of the 'globally threatened' Aquatic Warbler revealed by geolocators. Journal of Ornithology 154:549–552.

Streby, H. M., and D. E. Andersen (2013). Survival of fledgling Ovenbirds: Influences of habitat characteristics at multiple spatial scales. The Condor 115:403–410.

Streby, H. M., J. P. Loegering, and D. E. Andersen (2012). Spot mapping underestimates song-territory size and use of mature forest by breeding Golden-winged Warblers in Minnesota, USA. Wildlife Society Bulletin 36:40–46.

Streby, H. M., S. M. Peterson, C. F. Gesmundo, M. K. Johnson, A. C. Fish, J. A. Lehman, and D. E. Andersen (2013). Radio-transmitters do not affect seasonal productivity of female Golden-winged Warblers. Journal of Field Ornithology 84: 316–321.

Streby, H. M., J. M. Refsnider, S. M. Peterson, and D. E. Andersen (2014). Retirement investment theory explains patterns in songbird nest-site choice. Proceedings of the Royal Society of London, Series B 281:20131834. doi:10.1098/rspb.2013.1834

Stutchbury, B. J. M., S. A. Tarof, T. Done, E. Gow, P. M. Kramer, J. Tautin, J. W. Fox, and V. Afanasyev (2009). Tracking long-distance songbird migration by using geolocators. Science 323:896.

Sykes, P. W., Jr., J. W. Carpenter, S. Holsman, and P. H. Geissler (1990). Evaluation of three miniature radio transmitter attachment methods for small passerines. Wildlife Society Bulletin 18:41–48.

Townsend, J. M., C. C. Rimmer, and K. P. McFarland (2012). Radio-transmitters do not affect seasonal mass change or annual survival of wintering Bicknell's Thrushes. Journal of Field Ornithology 83:295–301.

White, G. C., and R. A. Garrott (1990). Analysis of Wildlife Radio-Tracking Data. Academic Press, San Diego, CA, USA.

Wu, J. X., D. M. Delparte, and P. J. Hart (2014). Movement patterns of a native and non-native frugivore in Hawaii and implications for seed dispersal. Biotropica 46:175–182.

Zenzal, T. J., Jr., R. H. Diehl, and F. R. Moore (2014). The impact of radio-tags on Ruby-throated Hummingbirds (*Archilochus colubris*). The Condor: Ornithological Applications 116:518–526.

THE CONDOR
Ornithological Applications

AmericanOrnithology.org

Volume 117, 2015, pp. 256–261
DOI: 10.1650/CONDOR-14-200.1

RESEARCH ARTICLE

Geolocators on Golden-winged Warblers do not affect migratory ecology

Sean M. Peterson,[1]* Henry M. Streby,[2] Gunnar R. Kramer,[1] Justin A. Lehman,[3] David A. Buehler,[3] and David E. Andersen[4]

[1] Minnesota Cooperative Fish and Wildlife Research Unit, Department of Fisheries, Wildlife, and Conservation Biology, University of Minnesota, St. Paul, Minnesota, USA
[2] Department of Environmental Science Policy and Management, University of California, Berkeley, California, USA
[3] Department of Forestry, Wildlife, and Fisheries, University of Tennessee, Knoxville, Tennessee, USA
[4] U.S. Geological Survey, Minnesota Cooperative Fish and Wildlife Research Unit, St. Paul, Minnesota, USA
* Corresponding author: sean.michael.peterson@gmail.com

Submitted December 2, 2014; Accepted February 17, 2015; Published April 29, 2015

ABSTRACT

The use of light-level geolocators is increasingly common for connecting breeding and nonbreeding sites and identifying migration routes in birds. Until recently, the mass and size of geolocators precluded their use on songbird species weighing <12 g. Reducing the mass of geolocators, such as by shortening or eliminating the light stalk, may make their deployment on small birds feasible, but may also inhibit their ability to receive light reliably, because small geolocators can be shaded by feathers. Here we report geolocator effects on migratory ecology of Golden-winged Warblers (*Vermivora chrysoptera*) in Minnesota and Tennessee. We also evaluated whether stalk length influenced precision of location data for birds on the breeding grounds. At 8–10 g, Golden-winged Warblers are the smallest birds to be outfitted with geolocators to date. We found no differences in return rates, inter-annual territory fidelity, or body mass between geolocator-marked individuals and a control group of color-banded individuals. We observed no difference in return rates or variation in estimated breeding locations between birds marked with stalked geolocators and those with stalkless geolocators. Our results suggest that some small songbirds can be safely marked with geolocators. Light stalks appear to be unnecessary for Golden-winged Warblers; the added mass and drag of stalks can probably be eliminated on other small songbirds.

Keywords: geologger, geolocation, light stalk, songbird, *Vermivora chrysoptera*

Los geo-localizadores no afectan la ecología migratoria de *Vermivora chrysoptera*

RESUMEN

El uso de geo-localizadores con detectores de nivel de luz es cada vez más común para conectar los sitios reproductivos y no reproductivos y para identificar las rutas migratorias de las aves. Hasta hace poco, el peso y el tamaño de los geo-localizadores no permitía su uso en especies de aves canoras que pesaran <12 g. La reducción del peso de los geo-localizadores, mediante el acortamiento o la reducción de las varillas lumínicas, puede hacer que sea posible su colocación a pequeñas aves, pero también puede inhibir su capacidad para recibir la luz de modo confiable, debido a que los pequeños geo-localizadores pueden ser tapados por las plumas. Aquí describimos los efectos de los geo-localizadores en la ecología migratoria de *Vermivora chrysoptera* en Minnesota y Tennessee. También evaluamos si el largo de las varillas lumínicas influencia la precisión de los datos de localización de las aves en los sitios reproductivos. *V. chrysoptera* pesa entre 8 y 10 g, siendo hoy en día el ave más pequeña a quién puede colocarse un geo-localizador. No encontramos diferencias en las tasas de retorno, la fidelidad territorial inter-anual o el peso corporal entre individuos marcados con geo-localizadores y el grupo de individuos control marcados con anillos de colores. No observamos una diferencia en las tasas de retorno o en la variación en la estimación de las localidades reproductivas entre las aves marcadas con geo-localizadores con o sin varillas lumínicas. Nuestros resultados sugieren que algunas aves canoras pequeñas pueden ser marcadas de modo seguro con geo-localizadores. Las varillas lumínicas parecen ser innecesarias para *V. chrysoptera*; el peso adicional y la carga de las varillas pueden ser probablemente eliminados en otras aves canoras pequeñas.

Palabras clave: ave canora, geo-localizador, localización geográfica, varilla lumínica, *Vermivora chrysoptera*

INTRODUCTION

Many species of migrant songbirds are experiencing population declines (North American Bird Conservation Initiative 2009) and there is evidence that in some cases, population declines may not be related to conditions during the breeding season (Holmes 2007). To develop full life-cycle conservation strategies, it is important to identify wintering locations, migratory routes, and important stopover sites. Recent advances in technology have allowed many species' migrations to be tracked and nonbreeding locations to be identified for the first time. Satellite transmitters (e.g., Fuller et al. 1995) and GPS (Global Positioning System) transmitters (e.g., Bouten et al. 2012) are effective methods for accurately locating individuals nearly anywhere on the planet. However, these technologies require relatively large, heavy batteries to record and transmit location data in real time; the smallest currently available units are 1-g GPS transmitters that record 10 locations, but are currently unsuitable for smaller birds (i.e. <20 g).

Light-level geolocator technology (hereafter: geolocators) is an increasingly common method of identifying wintering locations of migratory songbirds (reviewed by McKinnon et al. 2013). Geolocators are archival data loggers that detect and record light. Once recovered, daily estimates of latitude and longitude can be derived by calculating solar noon, midnight, or both from archived light thresholds (i.e. sunrise and sunset) compared against an internal clock (Hill and Braun 2001, Ekstrom 2004, Stutchbury et al. 2009). Although geolocators require recapturing marked individuals and do not produce location estimates with the precision of satellite or GPS transmitters, they are one of the few methods currently available to answer questions about migratory connectivity and wintering locations of small songbirds. Despite increasingly widespread deployment on songbirds larger than ~20 g, geolocators have only recently reached a size appropriate for small songbirds, with deployment and recovery reported for three species <20 g, but no species <12 g (Bridge et al. 2013). As with many novel technologies, the impact of geolocators on marked individuals and potential biases in the resulting data have not yet been well addressed, especially for the smallest species.

Bridge et al. (2013) suggested that the light sensor of a geolocator must be elevated above the body of the bird (usually achieved with stalks >5 mm) to avoid potential shading of the sensor by feathers. To our knowledge, however, variation among location estimates derived from stalked versus stalkless geolocator units has not been evaluated. Bowlin et al. (2010) estimated the aerodynamic cost of stalkless geolocators on birds and found that increased drag reduced the flight capabilities of birds more than the effects of attaching additional mass. Bowlin et al. (2010) estimated a potential decrease in flight range (i.e. the distance an individual can fly given a known amount of fuel) of 14% for a 10-g species marked with a 0.5-g stalkless geolocator (5% of mean body mass). Flight range, especially of small songbirds, would likely be reduced even further with the addition of a stalk to a geolocator unit.

Some information has been synthesized on the effects of geolocators on birds, with conflicting results depending on taxa and attachment methods. In a meta-analysis of geolocator deployment on songbirds, Bridge et al. (2013) concluded geolocators have minimal effects on return rates. A separate meta-analysis reported an overall negative impact of geolocators on birds (Costantini and Møller 2013). However, the Costantini and Møller (2013) dataset included band-mounted geolocators on seabirds and raptors, which they determined had a larger impact than harness-mounted geolocators on songbirds. Geolocators have been reported to reduce productivity or body mass in Tree Swallows (*Tachycineta bicolor*; Gómez et al. 2014), Barn Swallows (*Hirundo rustica*; Scandolara et al. 2014), and Northern Wheatears (*Oenanthe oenanthe*; Arlt et al. 2013). Negative impacts of other markers on songbirds often go unpublished (Hill and Elphick 2011), suggesting the negative geolocator effects reported so far do not represent a comprehensive assessment.

We conducted a controlled assessment of the ability of Golden-winged Warblers (*Vermivora chrysoptera*) to carry geolocators to and from their wintering grounds. At ~9 g, Golden-winged Warblers are the smallest species to date to be used in a geolocator study (Bridge et al. 2013, McKinnon et al. 2013). We tested the effects of geolocators on return rates, territory fidelity, and body mass by comparing birds with geolocators to a color-banded control group at 2 study areas. To assess the necessity of a light stalk, we compared differences in mean spring arrival date and precision of location estimates between stalked and stalkless geolocators.

METHODS

In May 2013, we geolocator-marked Golden-winged Warblers in the North Cumberland Wildlife Management Area in Campbell County, Tennessee, USA (36.2°N, 84.2°W) and Rice Lake National Wildlife Refuge (NWR) in Aitkin County, Minnesota, USA (46.5°N, 93.3°W). We captured breeding male Golden-winged Warblers in mist nets using call playback of conspecific vocalizations. When possible, we avoided targeting individuals after 0900 hr to reduce the likelihood that we would capture an individual outside of its territory (Streby et al. 2012). We banded all birds with standard U.S. Geological Survey aluminum legbands and 1–3 plastic color legbands. We recorded body mass using a digital scale to the nearest 0.01 g and recorded all capture locations using handheld GPS units (GPSMAP 76 or eTrex Venture HC Global Positioning System; Garmin, Schaffhausen, Switzerland), averaging locations using 100 points to achieve <5 m accuracy. At each site, we attached 20 geolocators (10 with a 5-mm light stalk and 10 stalkless; model ML6240; Biotrack, Wareham, UK) using the tracking-device attachment technique described in Streby et al. (2015), a modification of the Rappole and Tipton (1991) leg-loop harness design. Geolocators with harnesses weighed 0.51 g (stalked; 5.7% of mean body mass; 5.0–6.2% of individual body mass) or 0.45 g (stalkless; 5.0% of mean body mass; 4.7–5.6% of individual body mass). We considered all other color-banded, male Golden-winged Warblers at our sites to be control birds ($n = 12$ in Tennessee and $n = 20$ in Minnesota).

In May 2014, we initiated searches for both control and geolocator-marked individuals within 500 m of their 2013 capture location. Because no individual was resighted >150 m from its 2013 capture point, we ceased systematic searching efforts after 500 m due to logistical constraints. We used the same methods as during initial capture to recapture and record body mass and capture location for both geolocator-marked and control individuals. We confirmed the identities of any individuals that we did not recapture using their unique color-band combination and, for geolocator-marked birds, visually confirming the presence of a geolocator.

Statistical Analyses

We used ArcGIS 10.0 Geographic Information System (GIS) software (Environmental Systems Research Institute, Redlands, California, USA) to measure the distances between capture locations from 2013 and recapture locations from 2014. Because we did not record the mass or location of the majority of control birds in Tennessee, we used a Student's t-test to compare the annual change in capture location and annual change in mass between geolocator-marked and control birds using only individuals captured in Minnesota. We compared return rates between all geolocator-marked and control birds using a chi-square test of independence. We used logistic regression to assess the impact of the explanatory variable of mass at time of geolocator attachment on return rates with a generalized linear model in R (ver. 2.14.1, R Foundation for Statistical Computing, Vienna, Austria). We used a Z-test to determine if regression coefficients were significantly different from zero.

We compared return rates between Golden-winged Warblers equipped with stalked versus stalkless geolocators using a chi-square test of independence. We compared the annual change in mass and annual change in capture location between birds marked with stalked geolocators and those marked with stalkless geolocators using Student's t-tests. We used BASTrak (Biotrack, Wareham, UK) to download and analyze data from geolocators using the methods described in Delmore et al. (2012). We assessed the precision of breeding location estimates (i.e. the distance between geographic mean location and all daily locations estimated from unedited geolocator data) with ArcGIS 10.0 GIS software using unedited noon location estimates from 45 days of the 2013 breeding season (May 16–June 29 in Tennessee and June 1–July 15 in Minnesota) when birds were most likely to remain near capture locations. We compared the mean variation (i.e. the average distance from each estimated location to the mean estimated location) between stalked and stalkless geolocators using a Student's t-test. We used geolocator-based daily location estimates to identify the mean spring arrival date in 2014 for each recaptured geolocator-marked Golden-winged Warbler. We considered all statistical tests to be significant at an α level of 0.05.

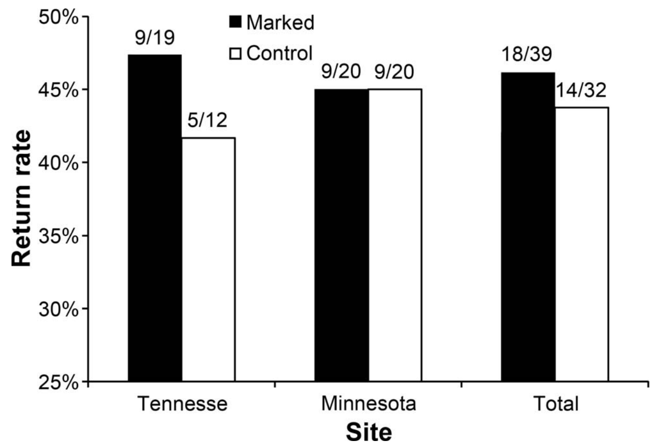

FIGURE 1. 2014 return rates of male Golden-winged Warblers marked with geolocators compared with color-banded–only control individuals in the Cumberland Mountains, Tennessee, and Rice Lake National Wildlife Refuge, Minnesota.

RESULTS

In 2014, we detected 19 Golden-winged Warblers that we had geolocator-marked the previous year ($n = 40$). One of those birds in Tennessee returned without a geolocator or harness, and we censored that bird from analysis because it was not possible to know when the geolocator detached. In total, we resighted 47% (9 of 19) of geolocator-marked birds that returned in Tennessee and 45% (9 of 20) of geolocator-marked birds that returned in Minnesota (Figure 1). We recaptured 6 of those 9 geolocator-marked birds in Tennessee. Of the 3 geolocators we did not recover, we were unsuccessful in capturing 2 individuals despite $\geq$5 extensive recapture attempts on separate days throughout the nesting season. We observed one additional individual with its geolocator on 2 occasions in late April but were unable to locate that individual once recapture efforts began in early May. We recaptured all 9 geolocator-marked birds that we resighted in Minnesota. All 15 recaptured geolocators successfully collected daily light data and 13 geolocators (87%) exceeded the expected

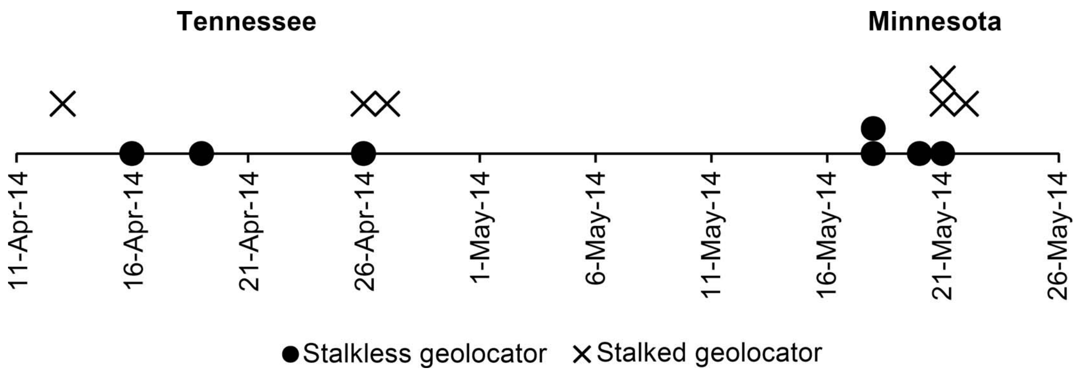

FIGURE 2. 2014 arrival dates of male Golden-winged Warblers carrying stalked and stalkless geolocators in the Cumberland Mountains, Tennessee, and Rice Lake National Wildlife Refuge, Minnesota.

unit battery life and recorded arrival from spring migration. We observed 42% (5 of 12) of the control birds in Tennessee and 45% (9 of 20) of the control birds in Minnesota. Overall return rates did not differ between geolocator-marked and control birds (Figure 1; $\chi^2 = 1.97$, df $= 1$, $P = 0.84$). Change in body mass from 2013 to 2014 in Minnesota was similar between 9 geolocator-marked birds ($\bar{x} = +0.16$ g) and 8 control birds for which we recorded mass in both years ($\bar{x} = +0.43$ g; $t = -0.68$, $P = 0.25$). Mass at the time of geolocator attachment was not related to return rates ($Z = -0.98$, df $= 35$, $P = 0.33$) for 17 returning birds ($\bar{x} = 8.88$ g) and 20 birds that did not return ($\bar{x} = 9.02$ g). We observed no difference in inter-annual territory fidelity, with similar mean changes in capture location for 9 geolocator-marked birds ($\bar{x} = 66$ m) and 9 control birds ($\bar{x} = 62$ m; $t = 0.99$, $P = 0.83$) in Minnesota.

Fifty-six percent (5 of 9) of birds carrying stalked geolocators and 40% (4 of 10) carrying stalkless geolocators returned in Tennessee. Thirty percent (3 of 10) of birds carrying stalked geolocators and 60% (6 of 10) carrying stalkless geolocators returned in Minnesota. Return rates did not differ between stalked (42%) and stalkless geolocators (50%; $\chi^2 = 0.77$, df $= 1$, $P = 0.62$). The change in mean mass also did not differ between 3 birds with stalked geolocators ($\bar{x} = +0.05$ g) and 6 birds with stalkless geolocators ($\bar{x} = +0.21$ g; $t = 0.36$, $P = 0.64$) in Minnesota. Similarly, the distance between the capture location and recapture location did not differ for 3 birds with stalked geolocators ($\bar{x} = 33$ m) and 6 birds with stalkless geolocators ($\bar{x} = 83$ m; $t = -1.29$, $P = 0.12$) in Minnesota. Mean distance of unedited daily location estimates from geographic mean estimate of 2013 breeding locations was 167 km for Golden-winged Warblers equipped with stalkless geolocators ($n = 7$) and 162 km for those equipped with stalked geolocators ($n = 6$; $t = 0.37$, $P = 0.64$). Mean spring arrival dates were similar between birds carrying stalked (Tennessee = April 22, Minnesota = May 21; Figure 2) and stalkless geolocators (Tennessee = April 20, Minnesota = May 20; Figure 2).

DISCUSSION

Ours is the first study we are aware of to investigate the effects of geolocators on songbirds weighing <12 g and the first to assess differences between stalked and stalkless geolocators. Due to the relatively small sample sizes in our study, the statistical power of our evaluations is limited. However, our results suggest that songbirds weighing as little as 9 g can successfully carry geolocators, and we observed no measurable impacts on return rates, body mass, or migration chronology, which are the parameters most likely to be negatively affected in small birds carrying markers. With the mass of geolocators and other markers decreasing nearly annually, the number of studies on small songbirds using these markers is likely to increase. Our results suggest that at least for some small songbirds, geolocator attachment is a viable method of obtaining unbiased information about migration and wintering areas.

As with any new marker or marking technique, it is important that the potential impacts of marking be evaluated. We did not observe any negative impacts on the parameters most likely to affect geolocator-marked Golden-winged Warblers in our study, but note that we did not assess potential impacts on other important parameters (e.g., reproductive success during and after carrying units). However, the impact of markers on Golden-winged Warblers is likely variable. A prior study showed no effects of radio-transmitters on productivity or survival of adult female Golden-winged Warblers on breeding sites (Streby et al. 2013). However, Chandler (2011) reported reduced return rates of wintering male Golden-winged Warblers when individuals carried radio transmitters into migration, suggesting that both the type of marker and the period when the marker is deployed may influence whether there are negative effects.

The stalkless geolocators we deployed were 0.06 g (12%) lighter and had a lower profile than stalked geolocators. Although we did not quantify the aerodynamics of either type of geolocator, stalkless geolocators were likely more aerodynamic than stalked geolocators; a factor that may be more important than mass for migrating songbirds (Bowlin et al. 2010). We observed no evidence that stalks negatively affected Golden-winged Warblers, suggesting they were capable of carrying the larger, less streamlined units. However, we found no evidence that light stalks increased the precision of location estimates for geolocators attached using a figure-eight backpack harness, and suggest that the likelihood of feather shading can be negligible using the attachment method described by Streby et al. (2015). Although neither geolocator configuration failed in our study, using stalkless units may also reduce the likelihood of unit failure due to stalk detachment (e.g., Rodríguez et al. 2009, Delmore et al. 2012, Renfrew et al. 2013). Furthermore, at least one study found that reducing the length of light stalks increased return rates in geolocator-marked individuals (B. Stutchbury, unpublished data reported in Bridge et al. 2013). Although we did not detect a difference in precision of location estimates derived from stalked versus stalkless geolocators, we suggest that this result needs to be experimentally tested for larger songbirds that have longer, denser feathers. We also suggest that further evaluations of the potential impacts of geolocators on small songbirds are necessary, and reporting of both negative and positive results in the published literature will aid in fully assessing application of this technology.

ACKNOWLEDGMENTS

We thank M. Barnes, J. Chancey, L. Coe-Starr, C. Colley, K. Eckert, C. Henderson, S. McLaughlin, and N. Seeger for assistance in the field, W. Ford and H. Saloka for logistical support, L. Schofield and 2 anonymous reviewers for comments improving the final product. Use of trade names does not imply endorsement by the U.S. Geological Survey, University of Minnesota, University of Tennessee, or any other organization supporting this research.

Funding: These data were collected during a project funded by the U.S. Fish and Wildlife Service and U.S. Geological Survey through Research Work Order No. 98 at the U.S. Geological Survey, Minnesota Cooperative Fish and Wildlife Research Unit; by the National Science Foundation through Postdoctoral Research Fellowship No. 1202729 (H. Streby); and by the U.S.D.A. Natural Resources Conservation Service in a grant administered by Jeff Larkin (Indiana University of Pennsylvania).

Ethics statement: We captured, marked, and collected data from birds following Protocol No. 561, approved by the University of Tennessee Institutional Animal Care and Use Committee and Protocol No. 1004A80575, approved by the University of Minnesota Institutional Animal Care and Use Committee.

LITERATURE CITED

Arlt, D., M. Low, and T. Pärt (2013). Effect of geolocators on migration and subsequent breeding performance of a long-distance passerine migrant. PLOS One 8:e82316. doi: 10.1371/journal.pone.0082316.

Bouten, W., E. W. Baaij, J. Shamoun-Baranes, and K. C. J. Camphuysen (2012). A flexible GPS tracking system for studying bird behaviour at multiple scales. Journal of Ornithology 154:571–580.

Bowlin, M. S., P. Henningsson, F. T. Muijres, R. H. E. Vleugels, F. Liechti, and A. Hedenström (2010). The effects of geolocator drag and weight on the flight ranges of small migrants. Methods in Ecology and Evolution 1:398–402.

Bridge, E. S., J. F. Kelly, A. Contina, R. M. Gabrielson, R. B. MacCurdy, and D. W. Winkler (2013). Advances in tracking small migratory birds: A technical review of light-level geolocation. Journal of Field Ornithology 84:121–137.

Chandler, R. B. (2011). Avian ecology and conservation in tropical agricultural landscapes with emphasis on *Vermivora chrysoptera*. Ph.D. dissertation, University of Massachusetts, Amherst, MA, USA.

Costantini, D., and A. P. Møller (2013). A meta-analysis of the effects of geolocator application on birds. Current Zoology 59:697–706.

Delmore, K. E., J. W. Fox, and D. E. Irwin (2012). Dramatic intraspecific differences in migratory routes, stopover sites and wintering areas, revealed using light-level geolocators. Proceedings of the Royal Society of London, Series B 279: 4582–4589.

Ekstrom, P. A. (2004). An advance in geolocation by light. Memoirs of the National Institute of Polar Research 58:210–226.

Fuller, M. R., W. S. Seegar, and P. W. Howey (1995). The use of satellite systems for the study of bird migration. Israel Journal of Zoology 41:243–252.

Gómez, J., C. I. Michelson, D. W. Bradley, D. Ryan Norris, L. L. Berzins, R. D. Dawson, and R. G. Clark (2014). Effects of geolocators on reproductive performance and annual return rates of a migratory songbird. Journal of Ornithology 155:37–44.

Hill, J. M., and C. S. Elphick (2011). Are grassland passerines especially susceptible to negative transmitter impacts? Wildlife Society Bulletin 35:362–367.

Hill, R. D., and M. J. Braun (2001). Geolocation by light level. In Electronic Tagging and Tracking in Marine Fisheries (J. R. Sibert and J. L. Nielsen, Editors). Springer, Dordrecht, Netherlands. pp. 315–330.

Holmes, R. T. (2007). Understanding population change in migratory songbirds: Long-term and experimental studies of Neotropical migrants in breeding and wintering areas. Ibis 149:2–13.

McKinnon, E. A., K. C. Fraser, and B. J. M. Stutchbury (2013). New discoveries in landbird migration using geolocators, and a flight plan for the future. The Auk 130:211–222.

North American Bird Conservation Intiative (2009). The State of the Birds, United States of America. U.S. Department of the Interior, Washington, DC, USA.

Peterjohn, B. G., J. R. Sauer, and C. S. Robbins (1995). Population trends from the North American Breeding Bird Survey. In Ecology and Management of Neotropical Migratory Birds: A

Synthesis and Review of Critical Issues (D. M. Finch and T. E. Martin, Editors). Oxford University Press, New York, NY, USA. pp. 3–39.

Rappole, J. H., and A. R. Tipton (1991). New harness design for attachment of radio transmitters to small passerines. Journal of Avian Biology 62:335–337.

Renfrew, R. B., D. Kim, N. Perlut, J. Smith, J. Fox, and P. P. Marra (2013). Phenological matching across hemispheres in a long-distance migratory bird. Diversity and Distributions 19:1008–1019.

Rodríguez, A., J. J. Negro, J. W. Fox, and V. Afanasyev (2009). Effects of geolocator attachments on breeding parameters of Lesser Kestrels. Journal of Field Ornithology 80:399–407.

Scandolara, C., D. Rubolini, R. Ambrosini, M. Caprioli, S. Hahn, F. Liechti, A. Romano, M. Romano, B. Sicurella, and N. Saino (2014). Impact of miniaturized geolocators on Barn Swallow *Hirundo rustica* fitness traits. Journal of Avian Biology 45:1–7.

Streby, H. M., J. P. Loegering, and D. E. Andersen (2012). Spot-mapping underestimates song-territory size and use of mature forest by breeding Golden-winged Warblers in Minnesota, USA. Wildlife Society Bulletin 36:40–46.

Streby, H. M., S. M. Peterson, C. F. Gesmundo, M. K. Johnson, A. C. Fish, J. A. Lehman, and D. E. Andersen (2013). Radio-transmitters do not affect seasonal productivity of female Golden-winged Warblers. Journal of Field Ornithology 84: 316–321.

Streby, H. M., T. A. McAllister, S. M. Peterson, G. R. Kramer, J. A. Lehman, and D. E. Andersen (2015). Minimizing marker mass and handling time when attaching radio-transmitters and geolocators to small songbirds. The Condor: Ornithological Applications 117:249–255.

Stutchbury, B. J. M., S. A. Tarof, T. Done, E. Gow, P. M. Kramer, J. Tautin, J. W. Fox, and V. Afanasyev (2009). Tracking long-distance songbird migration by using geolocators. Science 323:896.