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Abundance estimates to inform butterfly management: double-observer versus distance sampling

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Abstract Abundance estimates are used to establish baselines, set recovery targets, and assess management actions, all of which are essential aspects of evidence-based natural resource management. For many rare butterflies, these estimates do not exist, and conservation decisions rely instead on expert opinion. Using Bartram's scrub-hairstreak (*Strymon acis bartrami*, US Endangered) as a case study, we present a novel comparison of two methods that permit the incorporation of detection probabilities into abundance estimates, distance sampling and double-observer surveys. Additionally we provide a framework for establishing a systematic sampling scheme for monitoring very rare butterflies. We surveyed butterflies monthly in 2013, increasing intensity to weekly when butterflies were detected. We conducted 19 complete, island-wide surveys on Big Pine Key in the Florida Keys, detecting a total of 59 Bartram's scrub-hairstreaks across all surveys. Peak daily abundances were similar as estimated with distance sampling, 156 butterflies (95 % CI 65–247), and double-observer, 169 butterflies (95 % CI 65–269). Selecting a method for estimating abundance of rare species involves evaluating trade-offs between methods. Distance sampling requires at least 40 detections, but only one observer, while double-observer requires only 10 detections, but two observers. Double-observer abundance estimates agreed with distance sampling estimates, which suggests that double-observer is a reasonable alternative method to use for estimating detection probability and abundance for rare species that cannot be surveyed with other, more commonly used methods.

Keywords Butterfly · Abundance estimation · Hairstreak · Double observer · Distance sampling · Conservation · Management · Endangered species

Introduction

Rigorous abundance estimates are necessary to establish baselines, set recovery targets, and assess management actions, all of which are essential aspects of evidence-based natural resource management. Despite the obvious need for high quality data, management goals and conservation actions are often informed by anecdotal or biased information that may ultimately hinder recovery efforts (Abbitt and Scott 2001; Clark et al. 2002; Gerber and Hatch 2002). In North America, few butterfly species are formally protected, and many are understudied (Schultz and Hammond 2003). Quantitative abundance estimates exist for very few of the 26 butterfly species listed as endangered or threatened by the United States Fish and Wildlife Service (USFWS) (e.g. Brown and Boyce 1998; Hamm 2013; Henry et al. 2015). One explanation for this deficiency is that common methods for estimating animal abundance (distance sampling, mark-recapture, occupancy models) can present numerous challenges when applied to rare butterflies. These methods may underestimate abundance, injure butterflies, or be too time consuming or cost-prohibitive to routinely implement (Nowicki et al. 2008; Bried

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and Pellet 2012; Hamm 2013). Quantitative methods also have strict assumptions and sample size requirements that may be difficult to meet with very rare species. We present a novel comparison of two abundance estimation methods, double-observer and line transect distance sampling, which result in rigorous abundance estimates. We test these methods on Bartram's scrub-hairstreak (*Strymon acis bartrami*; Lepidoptera, Lycaenidae), the most recent butterfly to be listed as endangered by the USFWS (2014b).

Previous Bartram's scrub hairstreak surveys included informal walks, timed-meander counts, and modified Pollard–Yates transects (Hennessey et al. 1992; Salvato 2003). These surveys were efficient, documented the butterfly's historic range, and established local indices of population size (Schwartz 1987; Hennessey et al. 1992; Emmel et al. 1995; Salvato 1999; Salvato and Salvato 2010). When transects are arranged systematically, Pollard–Yates indicies (Pollard and Yates 1993) are correlated to abundance and can be used to compare relative abundances and trends over time at local scales (Thomas 1983). However, methods such as informal walks and Pollard–Yates transects lack the rigor necessary to generate unbiased abundance estimates and confidence intervals around estimates (Haddad et al. 2008; Issac et al. 2011). Another shortcoming of these methods is that when implemented in the field, survey routes are often located along features that are easy to access (i.e. established trails and fire breaks), and therefore may not be representative of available habitat in the landscape. This strategy works for large-scale monitoring programs—such as the UK butterfly monitoring scheme (www.ukbms.org)—that aim to answer questions about how land-use and climate change affect butterfly populations across a large geographic range (Franco et al. 2006; Menendez et al. 2007; Cayton et al. 2015; Oliver et al. 2015). However, when the goal is to estimate population size of a rare species with restricted range, transects must be systematically arranged so they are representative of available habitat (Brown and Boyce 1998; Buckland et al. 2001; Anderson 2001). Additionally, predefined transects are often located in what is presumed to be "high quality" habitat at year zero. For understudied species, "high quality" habitat is often a simple value judgment, rarely has the appropriate work been conducted to relate habitat variables to population size. Even with knowledge of what constitutes "high quality" habitat, population declines are "baked in" along pre-defined routes if habitat quality declines over time. This is particularly problematic for species that rely on dynamic habitats such as those maintained by disturbances such as fire. If population estimation is the goal of a particular survey effort, a systematic sampling scheme that encompasses all potential habitat is necessary (Anderson 2001).

Another limitation of Pollard–Yates transects and informal walks, is that these methods generally assume

perfect detectability which is rarely consistent through time and space (Harker and Shreeve 2008; Issac et al. 2011). Incorporating detection probability improves indices generated by survey counts by accounting for individuals that were *not* detected during the survey. Detection probability is the product of two components of detection, availability (a butterfly is available to be detected) and perception (an observer detects an available butterfly) (Johnson 2008). Availability is largely related to the behavior of the organism. For auditory bird surveys, this is important to consider since a bird that does not sing is not available to be detected. However, for butterflies, availability is less of an issue; we assume that if a butterfly is present in the survey area, it is available to be detected. Perception, on the other hand, is largely related to the observer and may be dependent on weather conditions, habitat features, distance from the observer, and observer experience/ability (Johnson 2008). This is the component of detection that we focus on in this paper.

A common method for estimating detection probability and population size is mark-recapture (Ehrlich and Davidson 1960; Haddad et al. 2008; Nowicki et al. 2008). Because this method requires recapturing a large number of individuals (Williams et al. 2002), and butterflies may be injured during the capturing and marking process (Murphy 1987), it is often impractical for monitoring federally protected butterfly species. Previous small-scale attempts to use mark-recapture with Bartram's scrub-hairstreak were unsuccessful because low densities of butterflies limited recapture rates (Emmel et al. 1995; Salvato 1999). Unlike mark-recapture, line-transect distance sampling and double-observer surveys are minimally invasive and relatively easy to implement. The key concept underlying distance sampling (Buckland et al. 2001) is that butterflies close to the observer are more likely to be detected than those that are far away. Detection probability can therefore be estimated by modeling the decline in the number of detections with distance as a detection function. One potential limitation of distance sampling is the need for at least 40 detections to accurately fit a detection function to data (Buckland et al. 2001). Detecting a sufficient number of butterflies is easy for common species, but much more difficult for rare species. Double-observer methods (Nichols et al. 2000; Alldredge et al. 2006) are predicated on the fact that two observers may simultaneously walk the same transect but not detect the same individual butterflies. This difference in observer detection history can then be used to estimate a detection probability. Double-observer methods can be applied when only 10 individuals are detected (Nichols et al. 2000), making this an attractive method for monitoring a species that occurs at low densities. The limitation inherent in the double-observer method is the need for two observers, which increases the cost of

surveys. Distance sampling is increasing in popularity for butterfly monitoring programs (Hicks 2011; Hamm 2013; Grundel 2015; Henry et al. 2015). Double-observer surveys, however, are rarely used in butterfly research but have been suggested as an alternative method for estimating butterfly abundance (Haddad et al. 2008; Nowicki et al. 2008).

We present, what is to our knowledge, the first comparison of butterfly abundance estimates produced by distance sampling to those produced by double-observer surveys. We evaluate the utility of each method in the context of endangered species monitoring. Additionally we provide a framework for establishing a systematic sampling scheme for monitoring very rare butterflies.

Methods

Study species and site

Bartram's scrub-hairstreak is a small (25 mm wingspan) grey butterfly endemic to pine rocklands of southern Florida and the lower Florida Keys (Baggett 1982; Smith et al. 1994; Salvato and Hennessey 2004). Females lay eggs singly on the racemes of its only known host, pineland croton (*Croton linearis*, hereafter referred to as croton) (Worth et al. 1996). The butterfly's distribution is closely tied to the distribution of croton (Schwartz 1987). Croton populations are restricted to pine rockland forests in south Florida. These forests once covered the Miami Rock Ridge that runs from North Miami Beach to Everglades National Park, and a few islands in the Florida Keys. In the last 100 years, 90 % of pine rockland has been cleared for development. Corresponding with the decline of its habitat, Bartram's scrub-hairstreak populations have dwindled and become increasingly fragmented (Smith et al. 1994; Salvato and Hennessey 2004; Anderson and Henry 2014). There are now only three extant populations of Bartram's scrub-hairstreak remaining in extreme southern Florida: within the Long Pine Key region of Everglades National Park, in pineland fragments of Miami-Dade County, and in the National Key Deer Refuge on Big Pine Key in the Florida Keys (Fig. 1; USFWS 2014a). In these areas, habitat loss is further magnified by degradation of remaining habitat caused by loss of disturbance. Disturbances, such as hurricanes or frequent low intensity fires, are necessary to maintain the open mid-story and canopy structure characteristic of pine rockland forest. Without disturbance, Bartram's scrub-hairstreak habitat, protected within Everglades National Park and the Key Deer Refuge, is vulnerable to forest succession (Alexander 1967).

No systematic survey of Bartram's scrub-hairstreak populations has been conducted to date. Therefore, both the listing process and land management actions are based on limited data (USFWS 2014a, b). We focused our surveys on the Big Pine Key population of Bartram's scrub-hairstreaks, which is the most isolated, located 100 km from populations in Everglades National Park. On Big Pine Key, croton has gone from being one of the 10 most common plants in pine rocklands in 1951 to being relatively rare, covering less than 0.01 % of pine rocklands in 2014 (Dickson 1955; Alexander and Dickson 1972; Folk 1992; Bradley and Saha 2009; Anderson and Henry 2014). In addition, croton has been extirpated from No Name and Little Pine Keys, both within the National Key Deer Refuge (Dickson 1955; Folk 1992; Carlson et al. 1993). This decline in croton is probably the result of a similar decrease in fire activity across Big Pine Key and other islands (Harley 2012). Efforts to restore, expand, and connect patches of croton-bearing pine rocklands through the use of mechanical clearing and prescribed fire, are necessary to prevent further declines and extirpation of the Big Pine Key population. Because of this, fine-scale butterfly data is needed to plan and assess the success of management actions.

Butterfly surveys

We defined potential Bartram's scrub-hairstreak habitat as the area occupied by croton on Big Pine Key. We acknowledge that this is a limited view of "habitat" (Dennis et al. 2003); however, our current knowledge of the butterfly's requirements is limited. We do know that Bartram's scrub-hairstreaks are known to be strongly associated with croton and are rarely found more than 5-m from a host plant (USFWS 2014b). Therefore, we identified potential habitat by delineating croton distribution across the island using croton count data from a 2007 pine rockland vegetation survey (Bradley and Saha 2009). In this survey, Bradley and Saha counted 260 croton plants in 57 of the 541 2.5-m radius plots sampled (see Bradley and Saha 2009 for detailed methods). We used ArcGIS 10.0 (ESRI) to interpolate these croton count values by distance in a 20 m-square grid across all public pine rockland habitat. From the resulting interpolated surface we extracted all grid cells likely to contain croton; we identified all cells containing >0.015 croton plants/ha. By choosing a very small cut-off value, we minimized our probability of missing areas with high croton density. We then visited each cell and eliminated those that did not contain croton. This process identified thirteen total hectares of potential Bartram's scrub-hairstreak habitat distributed across three core patches on Big Pine Key: the north (4.5 ha), central (6.5 ha), and south patches (2 ha). In each croton patch, we established a grid of parallel 50 m transects spaced 10 m apart, twice the furthest distance at
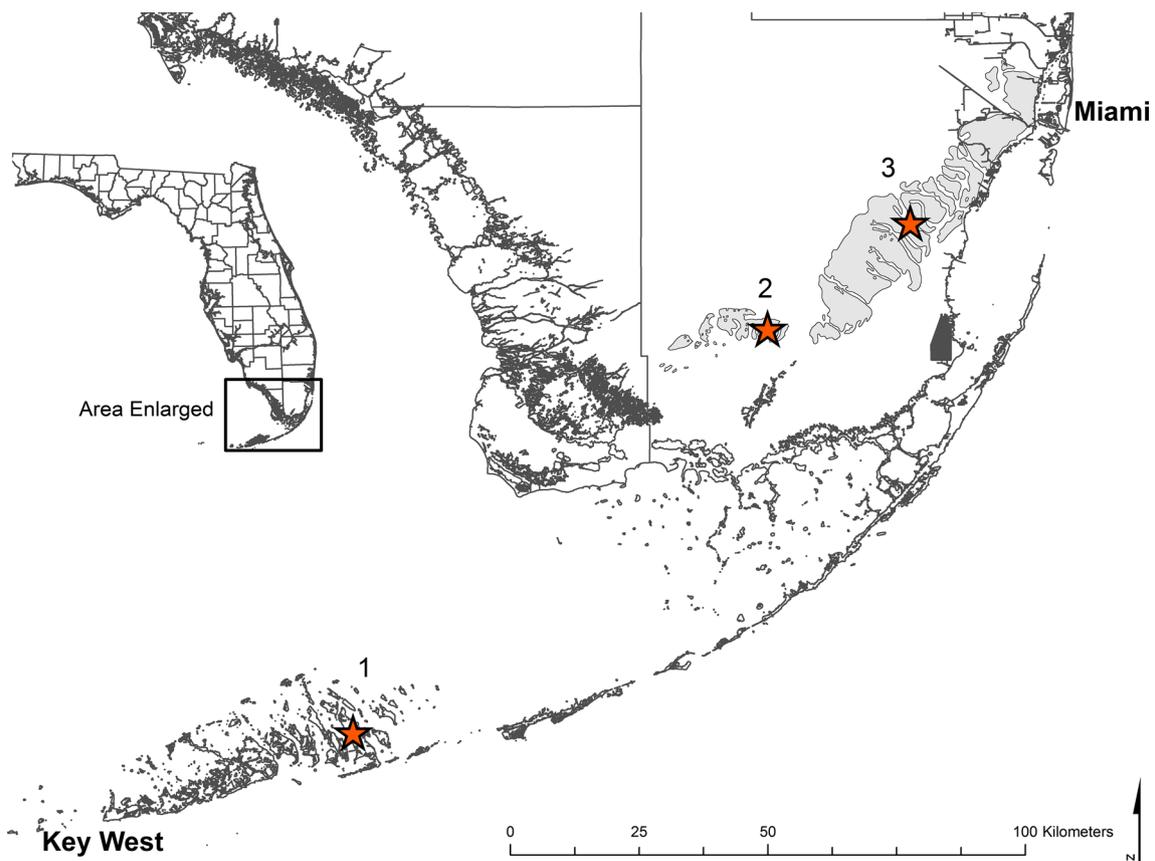
Fig. 1 Range map of historic pine rockland distribution (*grey shaded area*) and current Bartram's scrub-hairstreak populations (*stars*). *1* Big Pine Key, *2* Everglades National Park, *3* Miami-Dade County

which we were able to detect butterflies during informal walks. We oriented transects either north–south or east–west according to the shape of the patch (Fig. 2). On each survey date, we randomly selected one third of transects in each croton patch; this resulted in a sample of 20 transects in the north patch, 30 in the center patch, and 10 in the south patch.

To implement double-observer and distance sampling methods simultaneously, two observers concurrently walked each transect. When habitat allowed, observers walked side-by-side, if habitat forced observers to walk in single file, they alternated who led so as to not bias the detections of one observer over the other. The two key assumptions of distance sampling are that butterflies are detected at their initial locations and that distances are measured accurately. To meet these assumptions, for every butterfly detected, observers estimated perpendicular distance (to the nearest half-meter) from the transect line to the spot where the butterfly was first detected, whether in flight or perched, regardless of distance. We did not employ a cutoff distance for observations because observers tend to bias estimated distances to be within the cutoff, detecting more butterflies within that distance than were actually present during the survey and thus inflating density estimates (Simons et al. 2007). At the end of each transect, the two observers reconciled which butterflies were detected by observer A only, by observer B only, or by both observers. They did this by comparing where and when they detected each butterfly along the transect. This was possible due to the limited number of detections per transect (generally only 1, rarely more than 2). For butterflies detected by both observers, they determined who detected the butterfly first and recorded the detection distance estimated by that observer. The same two observers (EH and CA) conducted all surveys.

Bartram's scrub-hairstreaks have been detected on Big Pine Key in every month of the year and peak adult flight can vary from year to year. For this reason, we conducted monthly surveys from February–December 2013, increasing effort to weekly surveys when butterflies were present. All surveys were conducted between 0900 and 1530 h when temperatures ranged from 22 to 36 °C and winds were light to moderate (<7.7 ms^{-1}).

Fig. 2 Example habitat patches with transect grids. Gaps in transect grids result from wetlands and solution holes that do not contain croton and are therefore not included in the survey. **a** Example of patch with transects oriented north–south and **b** example of patch with transects oriented east–west
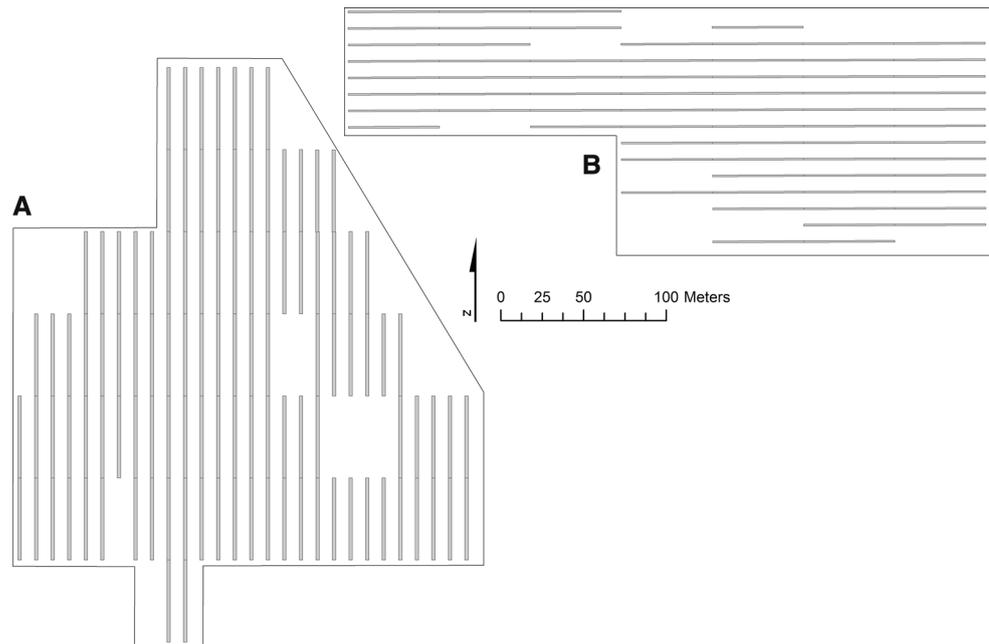
Data analysis

Distance

To estimate detection probability using distance sampling, we fit a detection function to our data that describes the decline in detection with distance from the transect. Buckland et al. (2001) recommend a minimum of 40 detections to accurately fit a detection function. Bartram's scrub-hairstreaks occur at low densities, and we did not detect 40 butterflies on any individual survey. Therefore, we pooled distance data from all butterflies detected by both observers during our 2013 surveys to create a global detection function that we then used to estimate butterfly density during the week of peak abundance. By pooling data, we assumed that detection probability is uniform across time and space. These are reasonable assumptions in our system because the butterflies occur in sub-tropical habitat where there are not dramatic vegetation changes across the year that would significantly affect detectability. Also, vegetation structure in all three habitat patches is similar in terms of attributes that could impede detection of butterflies, such as shrub cover (Anderson and Henry 2014). Using pooled data, we tested the following model/series expansion combinations in program DISTANCE: half normal model with cosine adjustment, half-normal model with hermite polynomial adjustment, and hazard rate model with simple polynomial adjustment (Buckland et al. 2001; Thomas et al. 2010). We used Akaike's information criterion (AIC$_c$) values and Chi square goodness-of-fit statistics to select the best model. We then applied this detection function to the detections from the week of the flight season during which we observed peak counts and estimated detection probability, effective strip width (the distance at which the observer misses as many butterflies as she or he detects) and peak daily density for Bartram's scrub hairstreaks.

Double-observer

Double-observer analysis focused on the week we recorded the highest island-wide counts. We used the multinomPois function in the "unmarked" package (Fiske and Chandler 2011) for R (v3.0; R Core Team 2014) to estimate detection probability and peak density (Kerry and Royle 2016) using data from the week during which we counted the most butterflies. This procedure assumes that observers counted all butterflies detected within a pre-defined transect width and estimates butterfly density-per-transect. Therefore, the definition of transect width is important for estimating density-per-area and total abundance. Instead of choosing an arbitrary width, we used the effective strip width estimated by DISTANCE as a guide and included only butterflies detected within our defined transect width. We do not anticipate that this strategy will conflate results from the two methods we are testing because each uses a different modeling framework to estimate detection probability, and it is the detection probability that is used to estimate abundances. If we are conflating the two methods, we expect double-observer methods to estimate lower densities than distance sampling because we are including area in our double-observer

survey where detection probability is expected to be as low as 0.5.

The multinomPois function assumes a multinomial distribution for the observation state (three possibilities: observer A, observer B, or both observers) and a Poisson distribution for butterfly abundance at each transect. To evaluate model fit, we used the parametric bootstrap (parboot) function to generate a Chi square statistic for the model. To estimate total daily butterfly density, we multiplied the per-transect density by transect area and converted units to butterflies per ha. Because we defined transect width using the effective strip width estimated by DISTANCE as a guide, we were able to directly compare Bartram's scrub hairstreak abundance estimates derived using distance sampling and double-observer methods.

Results

We conducted 19 complete, island-wide surveys between February and December 2013, detecting a total of 59 Bartram's scrub-hairstreaks across all surveys. Our goal was to complete at least one island-wide survey each month. Unfortunately, a government shut-down closed the wildlife refuge and eliminated our ability to survey in October. In November logistical constraints did not allow us to complete a survey; EH did conduct a single observer survey in November and did not detect butterflies. Throughout the year, we identified one major flight period between April 23 and May 23, 2013 (Fig. 3). During this flight period, we conducted 6 complete surveys in which
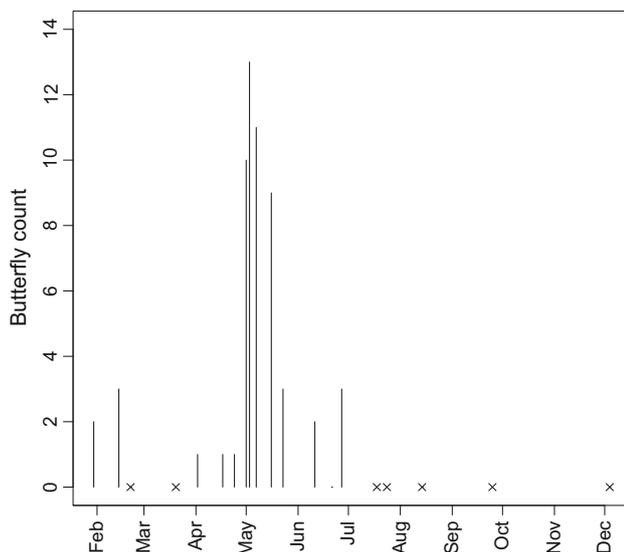

Fig. 3 Adult butterfly counts from island-wide surveys in 2013. Dates we conducted surveys but did not detect butterflies are indicated with an "X"

we, as a pair of observers, counted a total of 43 butterflies. Our peak count in one island-wide survey occurred on May 2 and 3, 2013. Bartram's scrub-hairstreak numbers began to decline shortly thereafter, by the end of June we no longer detected butterflies during surveys.

During our peak survey, each individual observer detected 9 butterflies in 7 (EH) and 8 (CA) transects. These counts translate to densities of 0.17 (95 % CI 0.044–0.30) and 0.17 (95 % CI 0.056–0.29) butterflies per transect, respectively, which scale to 8.7 (95 % CI 2.2–15.1) and 8.7 (95 % CI 2.8–14.5) butterflies per hectare (Table 1). Together, the pair of observers detected a total of thirteen butterflies during our peak count. These 13 detections were used for estimating peak density and abundance with both distance and double-observer methods.

Distance

Our best-supported model was the half normal model with cosine adjustment (χ^2 Goodness-of-fit p value = 0.35). The estimated detection probability was 0.3 (95 % CI 0.26–0.41) and estimated effective strip width was 1.83 m (95 % CI 1.42–2.37). Estimated density during peak flight was 12 (95 % CI 5–19) butterflies per hectare. We multiplied this density by 13 hectares, the total croton habitat surveyed on Big Pine Key, and estimated a peak daily abundance of 156 (95 % CI 65–247) Bartram's scrub-hairstreaks (Table 1).

Double-observer

Using the effective strip width of 1.83 m estimated by DISTANCE as a guide, we defined the width of our transects at 4 m (2 m on each side of the transect line). Both observers had the same detection probability of 0.67 (95 % CI 0.39–0.86). When combined, the detection probability of the pair of observers was 0.89 (95 % CI 0.62–0.98; Table 1). The bootstrapped Chi-square goodness-of-fit test was not significant ($p = 0.278$), confirming the model fit the data. The estimated detection probability translated to an abundance estimate of 0.26 (95 % CI 0.14–0.47) Bartram's scrub-hairstreaks per transect. This per-transect estimate translates to a density of 13 (95 % CI 5–21) butterflies per hectare, or a peak daily abundance estimate of 169 (95 % CI 65–269) Bartram's scrub-hairstreaks (Table 1).

Discussion

Our density and abundance estimates are the first for Bartram's scrub-hairstreak that utilize a systematic survey of potential habitat and incorporate detection probability.

Table 1 Comparisons of raw density and abundance estimates and those estimated using double-observer and distance sampling

	Detection probability	Butterflies/ha	Total daily abundance
Raw count (CA)	NA	8.7 (2.8–14.5)	112 (36–189)
Raw count (EH)	NA	8.7 (2.2–15.1)	112 (29–196)
Distance sampling	0.3 (0.26–0.43)[a]	12 (5–19)	156 (65–247)
Double-observer	0.89 (0.62–0.98)[b]	13 (5–21)	169 (65–269)

Numbers given are mean (95 % CI)

[a] Probability of detecting a butterfly given it is in the sampled area. In this case, sampled area extends to 5 m on either side of the transect; this is the farthest distance at which we detected a butterfly

[b] Probability that at least one of the two observers detects a butterfly along 4 m wide transect

Despite different approaches used in the estimation process, both double-observer and distance sampling analyses produced mean estimates of butterfly density that were functionally the same; the two estimates differed by only 8 %. Our sampling approach permits estimates of relative differences in butterfly numbers across patches as well as identification of hot spots of butterfly activity within patches. Understanding both abundance and distribution of butterflies across the landscape will allow land managers to better target future conservation actions where they can best benefit butterflies while minimizing possible harm.

Density estimates produced by the two methods were quite similar, but the two detection probabilities were not. Distance sampling estimated a detection probability of 0.3 while double-observer analysis estimated a combined detection probability of 0.89. This discrepancy results from the fact that the two methods are estimating average detection probabilities across different sized areas. The detection probability estimated by distance sampling is the average probability that a butterfly is detected between the transect line and the farthest detection distance—which in our case was 5-m—assuming perfect detection on the transect line. Double-observer analysis estimates the probability that at least one of the two observers will detect a butterfly on a transect of pre-defined width—which in our case was 4-m. Effectively, this equates to the difference between the probability of detecting a butterfly within a 500-m² transect (distance) and a 200-m² transect (double-observer). It is not surprising that these two methods produce different results given the difference in areas across which they estimate detection probability.

Our abundance estimates are *daily* abundance estimates, and are not *total* population size. The total population size would account for all adult butterflies that emerge over the course of an entire flight period. Estimating total population size requires knowledge of demographic parameters such as daily survival and generation time. These parameters could be estimated through a targeted mark-recapture study. However, given the small size of Bartram's scrub-hairstreak populations and the possibility of injury during

the marking process, such a study is currently unreasonable. With a time series of multiple butterfly abundance estimates per week during the flight period, total population size, and other demographic parameters, could be estimated using the model developed by Zonneveld (1991) and refined by Calabrese (2012). However, sampling multiple times per week during peak flight requires understanding the phenology of the butterflies, knowledge that is currently lacking.

To apply double-observer and distance sampling methods to species that occur at low densities, assumptions and necessary sample size requirements must be met. The most crucial assumption for a double-observer survey is that observers can easily reconcile observations at the end of each transect (Nichols et al. 2000; Alldredge et al. 2006). When species occur at high densities (>7 individuals/transect) reconciling observations could be difficult (Miller 1956). For these species, however, distance sampling is likely to be useful because detecting the minimum of 40 butterflies necessary for fitting detection functions is easily accomplished. At very high densities, however, it may become difficult to meet the distance sampling assumptions of detecting butterflies at their initial location and accurately estimating distances. Conversely, when species occur at low densities, the distance sampling target of 40 detections can be difficult to obtain. Therefore there is likely to be a mid-range of densities for which distance sampling is appropriate. Pooling data across multiple surveys and/or sites and developing a global detection function is one strategy that can be used to overcome the limitation of low densities (Henry et al. 2015). This approach assumes that detection probability of the target organism is constant across time and/or space. If this is unlikely to be true, pooling data can lead to biased abundance estimates. Bias, however, can be minimized by accounting for environmental variables likely to influence detection, such as temperature and wind, by only surveying under specific weather conditions. Additionally, environmental and habitat covariates can be incorporated into models of detectability. However, several detections across

a range of covariate values are necessary for this process, which may not be feasible for very rare species. In the case of Bartram's scrub hairstreak, management strategies designed to enhance the open structure characteristic of Bartram's scrub-hairstreak habitat will alter the vegetation in such a way that detection probability will differ between treatment areas and pooling data for distance sampling will no longer be appropriate.

It is important to acknowledge that our density estimates are highly variable. Density estimates have two components of variability, variability in detection probability and encounter rate. The variability in our distance sampling density estimates is mostly a result of variability in encounter rate (75 %) versus detection probability (25 %). This is driven by the distribution of butterflies across transects during the peak survey data set used to estimate peak daily density. We see the same pattern in our double-observer estimates, with variability in detection probability being much lower than that in encounter rate of raw counts (Table 1). Two possibilities for reducing encounter rate variability are to (1) increase the number of transects sampled in each survey and (2) to include environmental covariates related to local habitat quality such as croton abundance (Ganey et al. 2004). Increasing sampling effort is possible, but will make the survey more expensive, especially if double-observer methods are implemented. Collecting covariate data could easily be added to the survey without greatly increasing survey effort, but, as mentioned above, several detections across a range of covariate values are necessary for this process, which may not be feasible for very rare species.

Noisy abundance estimates like ours will not be able to detect small declines in abundance over time. However, since transects are systematically placed throughout all potential habitat, we can assume that our raw index count scales with abundance (Thomas 1983). Therefore, until we have better information on the drivers of Bartram's scrub-hairstreak phenology and can target greater survey effort during periods of peak abundance, the raw index count will be the best way to track changes in Bartram's scrub-hairstreak populations over time. This is not to say that our highly variable abundance estimates are useless. By accounting for detection probability in our surveys, we now have a better understanding of the order of magnitude of the population size, as well as the detectability of Bartram's scrub-hairstreaks.

The fact that double-observer abundance estimates agreed with distance sampling estimates suggests that double-observer is a good alternative method to use for estimating detection probability and abundance for rare species that cannot be surveyed with other, more commonly used methods. In addition to Bartram's scrub-hairstreak, double-observer surveys could be implemented for

Dakota skipper (*Hesperia dacotae*, US Threatened), poweisheik skipperling (*Oarisma poweisheik*, US Endangered), and frosted elfin (*Callophrys irus*, Endangered in 11 US States). These are all species of conservation concern that occur in low densities and for which there are no published population estimates that incorporate detection probability. Instead, as for Bartram's scrub-hairstreak, listing and conservation actions are based on transect surveys or measures of patch occupancy (Bried et al. 2012; Pfitsch and Williams 2009; USFWS 2013). Ultimately, choosing a strategy for estimating abundance for a rare species involves evaluating the trade-offs between methods in terms of cost, ability to meet assumptions, and data requirements. While distance sampling requires only one observer, it may not be appropriate for very low-density species. Despite the fact that double-observer requires twice the effort, it may be justified when accounting for detectability is necessary.

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