

# Dewlap color variation in *Anolis sagrei* is maintained between habitats within islands of the West Indies

RAPHAËL SCHERRER<sup>1,3</sup> \*, COLIN M. DONIHUE<sup>1,4</sup>,  
R. GRAHAM REYNOLDS<sup>2</sup>, JONATHAN B. LOSOS<sup>1,4</sup> AND ANTHONY J. GENEVA<sup>1,5</sup>

<sup>1</sup> Department of Organismic and Evolutionary Biology and Museum of Comparative Zoology  
Harvard University, Cambridge, MA, USA

<sup>2</sup> Department of Biology, University of North Carolina Asheville, Asheville, NC, USA

<sup>3</sup> Current address: Groningen Institute for Evolutionary Life Sciences,  
Groningen, The Netherlands

<sup>4</sup> Current address: Department of Biology, Washington University, St. Louis, MO, USA

<sup>5</sup> Current address: Department of Biology, Center for Computational and Integrative Biology,  
Rutgers University–Camden, Camden, NJ, USA

## Abstract

Animal signals evolve in an ecological context. Moreover, locally adapting animal sexual signals can be especially important for initiating or reinforcing reproductive isolation during the early stages of speciation. Dewlap color in *Anolis* lizards can be highly variable between populations in relation to both biotic and abiotic adaptive drivers, albeit at relatively large geographical scales. Here, we investigated local adaptation of the dewlap across habitat-types at a small spatial scale, as this may give an indication of how conditions for the early stages of speciation may be met. We explored variation in dewlap coloration in the most widespread species of anole, *Anolis sagrei*, across three characteristic habitats spanning the Bahamas and the Cayman Islands. Using reflectance spectrometry as well as supervised machine learning, we found significant differences in spectral properties of the dewlap between habitats within small islands. Passive divergence in dewlap phenotype associated with isolation-by-distance did not explain our results. Instead, the observed patterns in dewlap coloration are more consistent with an adaptive explanation in these *A. sagrei* populations, as one would otherwise expect differences within islands to be erased by gene flow at such small geographical scales. These habitat-specific dewlap differences varied in magnitude and direction across islands, and may suggest a role of sexual selection in driving these local patterns. While at present, populations from these different habitats probably experience too much gene flow to follow distinct evolutionary lineages, should additional barriers arise between habitat-specific populations, the observed disruptive selection on dewlap coloration may facilitate ecological speciation.

**Keywords** — *Anolis*, reflectance, local adaptation, sexual signal, supervised machine learning

## Introduction

The staggering diversity of animal communication signals has long been of interest to evolutionary biologists. Animals use chemical, mechanical, electromagnetic, and visual signals to communicate in a wide variety of contexts, including, for example, competition for mates, species recognition, aposematism, and cooperation (Bradbury and Vehrencamp, 2011). A primary evolutionary factor shaping communication signals is the sensory system and behavior of their recipient(s) (the sensory drive hypothesis; Endler and McLellan 1988; Endler 1992, 1998). Over the past decades, scientists have established that signals evolve in an ecological context and are dependent on environmental conditions (Endler, 1992, 1993a,b). Just as different habitats may favor different combinations of eco-morphological traits to maximize performance and fitness (Arnold, 1983), they may also shape different forms of a signal, so as to maximize its transmission and detection (e.g. Seehausen 1997), or reduce its detection by unintended recipients such as predators (Endler, 1984, 1990, 1991;

\*Corresponding author: r.scherrer@rug.nl

37 Halfwerk et al., 2014). This selective pressure may drive the local adaptation of communication  
38 signals.

39 One potential barrier to the maintenance of localized signal divergence is the homogenizing  
40 effect of gene flow. Population genetics theory suggests that gene flow may counteract local  
41 adaptation between localities and prevent divergence altogether, especially at small spatial scales,  
42 because of the inflow of maladapted alleles or because of the breaking of linkage between coevolving  
43 loci (Felsenstein, 1976; García-Ramos and Kirkpatrick, 1997; Dieckmann and Doebeli, 1999;  
44 Lenormand, 2002; Hendry et al., 2007a). This has been confirmed empirically in systems such as  
45 stick-insects (Nosil and Crespi, 2004) and sticklebacks (Hendry et al., 2007b). Yet, examples of  
46 microgeographic adaptation, i.e. adaptation at smaller scales than the range of dispersal, exist,  
47 highlighting a high potential of some organisms to respond to selection in the face of gene flow  
48 (see Richardson et al. 2014 and references therein). Examples include small scale adaptation in  
49 fragmented areas in Australian fruit flies (Willi and Hoffmann, 2012), or local adaptation to pre-  
50 dation pressure in North American salamanders (Richardson and Urban, 2013). Therefore, despite  
51 evidence that local adaptation may be particularly difficult at small spatial scales where gene flow  
52 tends to cause adjoining populations to remain genetically homogeneous, the potential adaptive  
53 response of species traits, in particular communication signals, to localized differences in habitats  
54 remains relatively unknown (Richardson et al., 2014).

55  
56 Lizards of the neotropical genus *Anolis* are a model system for studying the eco-evolutionary  
57 dynamics of local adaptation and natural selection (Losos, 2009). A particularly conspicuous trait  
58 of anoles is their dewlap; an extensible flap of skin that is typically sexually dimorphic and used  
59 as a communication signal in courtship (Sigmund, 1983; Driessens et al., 2014, 2015), competi-  
60 tion (Losos, 1985; Macedonia and Stamps, 1994; Macedonia et al., 2013) as well as in predator  
61 deterrence (Leal and Rodríguez-Robles, 1995, 1997; Leal and Rodriguez-Robles, 1997). Dewlap  
62 characteristics vary widely among the approximately 400 species of the genus (Nicholson et al.,  
63 2007). Interspecific variation in dewlap coloration is implicated in species recognition (Rand and  
64 Williams, 1970; Williams, 1969; Williams and Rand, 1977; Losos, 1985; Macedonia and Stamps,  
65 1994; Fleishman, 2000; Macedonia et al., 2013), and possibly involved in speciation (Lambert et al.,  
66 2013; Geneva et al., 2015; Ng et al., 2017).

67  
68 Within species, studies have shown a link between variation in dewlap coloration and differ-  
69 ences in habitats or climatic conditions (Macedonia, 2001; Leal and Fleishman, 2002; Thorpe and  
70 Stenson, 2002; Thorpe, 2002; Leal and Fleishman, 2004; Vanhooydonck et al., 2009; Ng et al.,  
71 2012, 2013, 2016; Vanhooydonck et al., 2009; Driessens et al., 2017). Some studies suggest that  
72 those differences may be adaptive, and that dewlaps may have evolved to maximize detectability  
73 given local light conditions (Fleishman and Persons, 2001; Leal and Fleishman, 2002, 2004). Other  
74 studies testing this hypothesis, however, found no pattern (Fleishman et al., 2009; Ng et al., 2012;  
75 Macedonia et al., 2014).

76  
77 Previous studies investigating variation in anole dewlaps compared populations at relatively  
78 large geographical scales, e.g. between islands (Vanhooydonck et al., 2009; Driessens et al., 2017)  
79 or within large islands such as Puerto Rico (Leal and Fleishman, 2002, 2004) or Hispaniola (Ng  
80 et al., 2012, 2016). These large scales and marine barriers should reduce gene flow (Ng and Glor,  
81 2011; Lambert et al., 2013; Richardson et al., 2014; Ng et al., 2017). That said, examples do exist  
82 of divergence in dewlap coloration at smaller scales or between populations with high degrees of  
83 gene flow (Thorpe and Stenson, 2002; Thorpe, 2002; Stapley et al., 2011; Ng et al., 2016).

84  
85 The species *Anolis sagrei* is widespread across islands of the West Indies (Reynolds et al.,  
86 2020). It is a model organism in studies of local adaptation (Losos et al., 1994, 1997, 2001; Kolbe  
87 et al., 2012), biological invasion (Kolbe et al., 2008) and sexual selection (Tokarz, 2002; Tokarz  
88 et al., 2005; Tokarz, 2006; Driessens et al., 2014; Steffen and Guyer, 2014; Driessens et al., 2015).  
89 Between-island variation in the mainly orange-red color of its dewlap was shown to be better ex-  
90 plained by climatic variables (Driessens et al., 2017) than biotic factors such as sexual selection or  
91 predation pressure (Vanhooydonck et al., 2009; Baeckens et al., 2018). How intra-island differences  
92 in habitat may contribute to the diversity of dewlap coloration, however, remains unexplored, and  
93 may reveal new insights into the scale of local adaptation despite gene flow.

The island bank systems of the Bahamas and Cayman Islands presently, if not historically, comprise relatively small islands, with no major geographic barriers within islands limiting dispersal for this promiscuous species (Kamath and Losos, 2018). These islands all share three characteristic native West Indian habitat-types – beach scrub bush, closed-canopy primary coppice forest, and mangrove forest – that are often spatially intermingled. These habitats contrast in environmental parameters including vegetation community, light irradiance, humidity and temperature (Howard, 1950; Schoener, 1968). Each of these island groups (Caymans and Bahamas) has been colonized independently by *A. sagrei* from Cuba (Driessens et al. 2017; Reynolds et al. 2020, van de Schoot et al. unpubl.), such that these archipelagos constitute an ideal suite of natural replicates to explore within-island dewlap diversity across multiple islands.

Here, we analyzed the color characteristics of *A. sagrei* dewlaps within nine islands in the Bahamas and Cayman Islands, combining reflectance spectrometry and supervised machine learning. Our sampling design included sites in close proximity (the median distance between two sites within an island was 11.2km). We tested for divergence in dewlap phenotype between habitats within islands and between islands across the range of *A. sagrei*. We predicted that if light conditions in the environment indeed drive color evolution, dewlaps should be most similar between beach scrub and mangrove forest, which both have high levels of light irradiance, contrary to the darker, closed-canopy coppice forest. Similar, if detectability is maximized given the local conditions, we expected darker and more contrasting dewlaps in high irradiance habitats. Finally, if habitat characteristics are strong determinants of dewlap color variation, similar patterns should be observed across multiple islands (Losos, 2011). We found strong support for fine-scale, within-island differences in coloration between lizards inhabiting the three habitat-types in several color space dimensions, suggesting a potentially strong effect of divergent selection. However, the divergence patterns we observed did not match our *a priori* predictions and were inconsistent between islands. We found no evidence of isolation-by-distance as an explanation for the observed differences. Our results are nevertheless consistent with small-scale adaptive maintenance of signal polymorphism despite presumed considerable opportunity for gene flow, and might suggest that idiosyncracies of local drift, selection, and gene flow contribute to differing outcomes in different populations.

## Methods

### Data collection

We sampled 466 male *Anolis sagrei* from seven islands in the Bahamas Archipelago – Abaco, North Andros, South Andros, South Bimini, Eleuthera, Long Island, Ragged Island – and two in the Cayman Islands – Cayman Brac and Little Cayman (Figure 1). These islands and island banks were chosen to span the breadth of the West Indian range of *Anolis sagrei*, because they have highly similar habitat types, and because the *A. sagrei* on each island group are derived from ancient and distinct colonization events from Cuba (i.e. relatively evolutionarily independent, Reynolds et al. 2020). Three habitats were sampled on each island based on characterizations by Howard (1950) and Schoener (1968). Each habitat is clearly distinguishable by their dominant vegetation type — xeric coastal scrub (open, relatively dry habitat consisting of low vegetation or isolated trees), primary coppice forest (closed-canopy forest) and mangrove forest (wet coastal habitat with trees growing in brackish water and high light penetration). Sample sizes are given in Table S1. Our sampling design enabled us to test for differences between habitats at a coarse and fine geographical scale. The median distance between two localities within an island was 11.18km, with some islands being sampled at smaller or larger scales (Figure S1, Table S2). 80.3% of all pairwise distances within islands were below 50km. Additionally, there are no major barriers to dispersal (such as mountains or grassland) on any of the islands that we sampled.

### Reflectance measurements

We measured reflectance between 300 and 700nm wavelength, a range that encompasses the colors visible to most lizards and vertebrates in general (Lazareva et al., 2012). Measurements were taken with an Ocean Optics USB4000 spectrometer, a pulsed Xenon light source (PX-2, Ocean Optics, Largo, FL, USA) and a reflectance probe protected by a black anodized aluminum sheath.

148 Measurements were taken with a 45-degree inclination to prevent specular reflection (Endler, 1990).  
149 The device was regularly standardized with a Spectralon white standard (Labsphere, North Sutton,  
150 NH, USA). Reflectance was measured at the center of the dewlap.

## 151 Analysis

152 All analyses in this study were performed in R 3.6.1 (R Core Team, 2019).

### 153 Dimensionality reduction

154 Reflectance curves were smoothed using the R package pavo (Maia et al., 2013) as well as with  
155 custom R functions, down to one reflectance value at each nanometer in wavelength from 300  
156 to 700nm. Because neighboring wavelengths are highly collinear in reflectance, we reduced the  
157 dimensionality of the data using principal component analysis (PCA), as per Cuthill et al. (1999)  
158 and Leal and Fleishman (2002). We performed PCA on each island separately and systematically  
159 retained the first four principal components (PC), which together always explained more than  
160 88.8% of the variance across islands (Table S3). PC1 explained between 40 and 56% of the variance  
161 across islands; PC2 explained 17.4–27.9%; PC3 12.7–17.6% and PC4 4.3–10.5%. The first four PCs  
162 explained similar proportions of variance when calculated for all islands together (Table S3). PCs  
163 need not represent the same wavelengths across islands because they are fitted on different datasets.  
164 Nevertheless, PC1 was very collinear with brightness for all islands (Figure S2, Table S4). PC2  
165 correlated highly with the red and ultraviolet ends of the spectrum, which were inversely correlated  
166 with each other (Fig. 3A). Higher PCs corresponded to various combinations of wavelengths.  
167 Because PC1 correlated uniformly with all wavelengths across the spectrum we considered PC2  
168 onwards to capture the chromatic dimensions of color space, i.e. the relative contributions of the  
169 wavelengths regardless of brightness.

### 170 Pooled analyses

171 In addition to within-island PCA, we performed a PCA on pooled data from the whole archipelago.  
172 The first four principal components explained 91.3% of the variance (Table S3). Again PC1 strongly  
173 correlated with brightness (Fig. S3, Table S4). PC2 was positively correlated to short wavelengths  
174 (ultraviolet to blue) and negatively correlated to long wavelengths (green to red, Fig. S4B). PC3  
175 was strongly negatively correlated with UV reflectance and positively correlated with blue-green.  
176 PC4 was made of a mosaic of wavelengths, correlating positively with blue and red but negatively  
177 with ultraviolet and yellow.

178 We used this dataset to partition the variance in dewlap coloration among islands, habitats  
179 and habitats within islands, using a two-way multivariate analysis of variance (MANOVA) with  
180 an interaction term. However, because the assumptions of parametric MANOVA were violated  
181 for all islands but Ragged Island (multivariate normality, Henze-Zirkler's test, Henze and Zirkler  
182 1990, R package MVN, Korkmaz et al. 2014, Table S5; and homogeneity of covariance matrices,  
183 Box's M-test, Box 1949; Morrison 1988, R package heplots, Fox et al. 2018, Table S6), we used  
184 a semi-parametric MANOVA instead (R package MANOVA.RM, Friedrich et al. 2018), with P-  
185 values calculated from a bootstrap procedure with 1,000 iterations. We calculated the proportion  
186 of variance explained by islands, habitats and the habitat-by-island interaction using partial effect  
187 sizes  $\eta^2$  on a MANOVA-approximation of the analysis (R package heplots, Fox et al. 2018).

### 189 Machine learning

190 Because of the aforementioned violations of the MANOVA assumptions, and to reduce the chances  
191 of false discovery, we conducted multivariate group comparisons using support vector machines  
192 (SVMs), a model-free, powerful nonparametric supervised machine learning technique.

193 Machine learning for group comparison has become more popular in ecology and evolution in  
194 recent years (e.g. Pigot et al. 2020). In particular, SVMs are designed to find the best possi-  
195 ble nonlinear boundaries between labelled groups of points in multidimensional spaces, without  
196 assumptions about the distribution of the data (Cortes and Vapnik, 1995; Cristianini and Shawe-  
197 Taylor, 2000; Kim and von Oertzen, 2018). This makes them well suited to field biological data,

which often violate the assumptions of classical linear modeling (Kim and von Oertzen, 2018) and can be, as in the case of coloration, inherently highly multivariate (Cuthill et al., 1999). First, a machine is trained to recognize differences between groups within a subset of the data called the training set. Significance of differences is then assessed by testing the accuracy of that fitted machine in predicting the group-labels of data points that were not included in the training, called a testing set, based solely on their multivariate coordinates. This cross-validation procedure results in a proportion of correctly classified points, or generalization accuracy score, which can be compared to that expected under random guessing using a binomial test.

In this study, we performed SVM classifications on each island separately. We used a standard five-fold cross-validation procedure, where the data were randomly split into five bins of approximately equal sizes. Each bin was in turn taken as the testing set while the rest was used as a training set, thus resulting in five trained machines per cross-validation. We replicated this procedure 100 times for each island to account for stochastic outcomes. We performed binomial tests to evaluate the significance of deviations in observed mean generalization accuracy per island to null expectations under random guessing. Each training data set was downsampled to the size of its least represented habitat to ensure balanced training samples. We ensured that each habitat was represented by at least five data points in the training set.

All classification analyses were repeated using the more classical linear discriminant analysis (LDA), a supervised machine learning technique finding linear boundaries that maximize the differences between groups, albeit assuming multivariate normality and homogeneity of covariance matrices (Ripley, 1996). We used the R package rminer (Cortez, 2010, 2016) for SVMs, and MASS (Venables and Ripley, 2002) for LDAs. We used rminer's default heuristic search option to automatically tune the Gaussian kernel parameter  $\sigma$  and the complexity parameter  $C$  for the SVMs.

The same procedure was repeated on principal components from the whole archipelago (see Pooled analyses) to evaluate the significance of archipelago-wide differences in dewlap coloration across habitats.

All machine learning classifications performed on principal components were also repeated on the original reflectance datasets reduced to 50-nm spaced wavelengths from 300 to 700nm.

We conducted one-dimensional sensitivity analyses using rminer (Cortez and Embrechts, 2013) to determine the relative importance of the different input variables during classification where significant differences were detected, both on machines trained on principal components and machines trained on non-transformed reflectance at various wavelengths. In parallel, we conducted univariate analyses of variance to independently test the importance of different variables in between-habitat variation, on islands where the machines detected significant differences based on binomial tests (next section).

## Univariate analyses

For each island where significant differences in multivariate dewlap coloration were detected between habitats, we used multiple univariate analyses of variance (ANOVA) to identify which variables were responsible for the observed differences. We constructed our ANOVA models in two steps, as per Zuur (2009). In a first step, we accounted for heterogeneity of variances across groups by systematically comparing the goodness-of-fit of an ANOVA model estimated with ordinary least squares (OLS) with that of a model estimated with generalized least squares (GLS), which allowed one estimate of residual variance per habitat (using the R package nlme, Pinheiro and Bates 2000; Pinheiro et al. 2020). Both models were fitted with restricted maximum likelihood (REML). Goodness-of-fit was estimated using Akaike's Information Criterion corrected for small sample sizes (AICc, R package MuMIn, Bartoń 2019), and the estimation method yielding the lowest AICc was retained. In a second step, we re-fitted the retained model with maximum likelihood (ML) to test for the effect of habitat-type using likelihood ratio tests (LRT) between a model including a habitat-term and a null model lacking the habitat-term.

We tested the assumptions of the parametric ANOVA for each island included in the univariate analyses. For all islands where deviations from multivariate normality were detected in at least one

256 habitat (Table S5), we assessed univariate normality for each principal component (Shapiro-Wilk's  
257 test, Table S7). For skewed PCs that deviated significantly from normality, we repeated the analysis  
258 using a nonparametric Kruskal-Wallis test (Hollander et al., 2013). We found no multivariate  
259 outliers based on the Mahalanobis distance (package MVN, Korkmaz et al. 2014). We used the  
260 cases of better fit of the GLS model relative to the OLS model as evidence for heterogeneity of  
261 variances, which were then accounted for by the GLS approach (Table 1).

262

263 Significant *post hoc* contrasts were assessed using Tukey's Honest Significant Difference (HSD)  
264 test whenever the assumptions of normality and homogeneity of variances was met (Tukey, 1949),  
265 Dunnett's T3 method when only homogeneity of variances was violated but not normality (Dun-  
266 nett, 1980), and Nemenyi's test when normality was violated (Nemenyi, 1963). All *post hoc* tests  
267 were performed with the R package PMCMRplus (Pohlert, 2020).

268

269 We used the same procedure to investigate which variables, if any, were involved in archipelago-  
270 wide multivariate differences between habitats detected in our two-way MANOVA design (see  
271 Pooled analyses). However, in the first step or our model comparison procedure, we added mixed-  
272 effect equivalents of our OLS and GLS models, this time with island as a random effect. The  
273 resulting four models were compared and the best fitting variance structure was retained as ex-  
274 plained above.

## 275 Spatial autocorrelation

276 We tested for within-island spatial autocorrelation between the geographical distances among sam-  
277 pling sites and their Euclidean distances in multivariate color space (mean PC1 to PC4 per site,  
278 Table S2), regardless of habitat-type. Because often only a few sites were sampled per island, we  
279 could not get meaningful results from tests that use sites as units of observation, such as Moran's  
280 I test (Gittleman and Kot, 1990). Instead, we designed a permutation test where we randomly  
281 reshuffled individual lizards across sites within islands 1,000 times each, and systematically re-  
282 calculated Pearson's correlation coefficient between geographic distances (computed as geodesic  
283 distances in the R package geosphere; Hijmans 2019) and phenotypic distances. We used the re-  
284 sulting null distributions of correlation coefficients to assess the significance of the observed spatial  
285 autocorrelation for each island.

## 286 Site differences

287 In this study, we were interested in the minimum spatial scale at which significant differences  
288 between habitats could be detected within islands. We performed multiple pairwise nonparametric  
289 Wilcoxon-Mann-Whitney tests (Hollander et al., 2013) to compare dewlap coloration between  
290 sites with different habitat-types, for each pair of habitats and each variable where significant  
291 differences were detected with our analyses of variances. The P-values were adjusted using a  
292 Benjamini-Hochberg correction for multiple testing (Benjamini and Hochberg, 1995).

## 293 Results

294 We tested for variation in *A. sagrei* dewlap coloration between populations living in three charac-  
295 teristic habitat types across nine islands that span the West Indian range of the brown anole (Fig  
296 1, S1). We found that most of the variation in coloration is partitioned between islands (two-way  
297 semi-parametric MANOVA, modified ANOVA-type statistic (MATS) = 2009.6,  $P < 0.001$ , Fig.  
298 S5, explained variance  $\eta^2 = 44.3\%$ , MANOVA approximation). Nonetheless, we did find evidence  
299 for differences in dewlap coloration between habitat-types, and those were mostly island-specific  
300 (habitat-by-island interaction term, MATS = 384.4,  $P < 0.001$ , explained variance  $\eta^2 = 11.4\%$ ),  
301 leaving a small but significant portion of the variation explained by an archipelago-wide habitat  
302 effect (MATS = 42.5,  $P = 0.001$ ,  $\eta^2 = 4.8\%$ ).

303

304 The small archipelago-wide effect of habitat-type was detected for PC1, PC2 and PC3 (mixed-  
305 effect ANOVA with island as a random effect, Table S8), but this effect was too small for *post hoc*  
306 tests to find which habitats differed. Archipelago-wide differences in dewlap coloration between  
307 habitats were also detected by SVMs trained on pooled data regardless of island identity, both for

PCA data and reflectance scores (Fig. S6, S7). This pattern seemed to be driven by mangrove lizards being correctly reassigned more often than predicted by chance. Sensitivity analyses on these machines suggest a relatively small role of long wavelengths (red reflectance) in driving this pattern (Fig. S9), but did not reveal strong differences between the PCs in relative importance (Fig. S8). Archipelago-wide differences were not detected by LDA classifiers at all (Fig. S10, S11).

Within islands, SVM classifiers correctly assigned individuals to their habitat of origin based solely upon dewlap coloration on five islands: Abaco, Bimini, Cayman Brac, Little Cayman, and Long Island (Fig. 2). An LDA approach yielded similar success rates (Fig. S12), suggesting robust differences between these populations. Of the five islands, Little Cayman was the best discriminated with a mean SVM generalization success of 73.4% (Table S9). The results of the classification analyses on PCA data were very similar to results from SVMs and LDAs trained on reflectance values at 50nm-spaced wavelengths from 300 to 700nm (Fig. S13 and S14).

Differentiation in dewlap coloration occurred in multiple dimensions of color space. Moreover, the differences in dewlaps between habitats were not always consistent between islands, thus, we will discuss the habitat-specific variation in dewlap coloration for each island where significant differences were detected in turn (Fig. 3, Tables 1, S10). Figure 3A provides a key to map principal component scores to the underlying wavelengths.

On Abaco, dewlaps did not differ in PC1, which represents brightness. Mangrove lizards had significantly lower PC2 scores, corresponding to higher ultraviolet reflectance and lower red reflectance. Coastal beach scrub lizards had lower scores on PC3, corresponding to lower ultraviolet reflectance and higher blue reflectance.

On Bimini, coastal beach scrub lizards had significantly brighter dewlaps than lizards from mangroves (PC1), but mangrove lizards had higher PC2 scores than beach scrub lizards, indicating higher violet and blue reflectance, and lower red reflectance. Lizards from primary coppice had higher PC3 scores overall, which correlated very positively with ultraviolet reflectance.

On Cayman Brac, coppice-lizard dewlaps were significantly less bright than lizards from the other habitats. Coastal beach scrub lizards had dewlaps that scored low on PC2, corresponding to lower violet-blue and more red, while the mangrove lizards exhibited the opposite: relatively higher levels of violet-blue and less red. In PC3 space we found that dewlaps from lizards in the coastal habitat had high ultraviolet reflectance, coppice lizards had intermediate levels, and mangrove lizards had relatively low levels.

On Little Cayman, the dewlaps of coppice lizards were significantly darker (PC1) than coastal lizards. Mangrove lizards had less ultraviolet and redder dewlaps (PC2). The dewlaps of the coastal beach scrub lizards had higher levels of red and ultraviolet reflectance and less blue reflectance than the dewlaps of the other habitat-populations (PC3).

On Long Island, lizards from the coppice habitat had darker dewlaps than lizards from the other habitats (PC1). Coastal lizards had relatively more ultraviolet and less blue-green reflectance in their dewlaps (PC3). These coastal-habitat lizards also scored lower on PC4, corresponding to slightly more violet and green-yellow dewlaps, and less blue dewlaps, than the mangrove lizards on the island.

Sensitivity analyses on classifiers suggested an overall higher relative importance for PC2 and PC3 in determining between-group differences on Abaco, both in SVM and LDA classifiers (Fig. S15, S16), consistent with our ANOVA results (Fig. 3B). There was no strong signal of differences in relative importance among principal components on the other islands. Sensitivity analyses of SVMs trained on reflectance scores rather than principal components revealed, however, a consistently higher importance of ultraviolet reflectance in between-group differences on all islands (Fig. S17). This pattern was not recovered for LDAs trained on reflectance scores (Fig. S18).

We did not find significant spatial autocorrelation between the sampling sites on the islands where we detected a significant habitat effect. We did, however, detect a significant positive sig-

366      nal of autocorrelation on Eleuthera (Table S11), suggesting possible color differentiation through  
367      isolation-by-distance on this island.

368

369      In contrast, differences in dewlap coloration between habitats were often detected in close ge-  
370      ographical proximity. For example, Bimini, Cayman Brac, and Little Cayman were among the  
371      smallest islands in our study (Fig. S1). Indeed, most significant differences in dewlap coloration  
372      involved sites that were 5-10km apart. Our most extreme case of significant differences occurred  
373      for PC3 between a beach scrub site and a coppice site, separated from each other by a few hundreds  
374      of meters at most on Bimini (multiple pairwise Wilcoxon-Mann-Whitney tests, Fig. S19).

375

376      Patterns of differentiation were inconsistent across the five most significant islands. Contrasts  
377      in principal components between habitats, calculated on pooled data from the whole archipelago,  
378      were not similar, for any component, among islands (Fig. S20; MANOVA, Pillai's trace = 0.354,  
379       $F(6, 32) = 1$ , P = 0.36). No pattern of variation was shared by all five significant islands, along  
380      any dimension. Some patterns did seem more common however, such as darker dewlaps among  
381      coppice lizards (Cayman Brac, Little Cayman, and Long Island, Fig. 3) or the intermediate posi-  
382      tion of coppice lizards in chromatic color space (Cayman Brac and Long Island). In other cases,  
383      patterns of differentiation were reversed from one island to another, with more ultraviolet reflecting  
384      dewlaps in mangroves than in coastal habitat on Abaco and Cayman Brac, but the opposite on  
385      Little Cayman and Long Island. Overall, it seemed that patterns of heterogeneity of variance were  
386      often driven by higher variances in coloration within beach scrub lizards (Fig. 3, Table 1). Yet  
387      other patterns were idiosyncratic, such as the combination of higher red and ultraviolet reflectance  
388      in coastal lizards on Little Cayman, where the rule seemed to be a negative correlation between  
389      ultraviolet and red reflectance across every other island.

390

## 391      Discussion

392      **Dewlap coloration differs between habitat-types** We found that male dewlap coloration in  
393      *A. sagrei* significantly varied between fine-scale habitat-types (beach scrub bush, primary coppice  
394      forest and mangrove forest) on five islands of the West Indies: Abaco, Bimini, Cayman Brac, Little  
395      Cayman and Long Island. However, the habitat-specific variation in dewlaps was not consistent  
396      between these islands. Although those results are consistent with adaptation at a very local  
397      scale, other evolutionary drivers could be at work, such as phenotypic plasticity, random drift,  
398      or historical contingency, including multiple colonization events. We reject this last explanation  
399      because all of the island populations in this study are strictly monophyletic, implying a single  
400      colonization event per island (van de Schoot, unpublished thesis; Driessens et al. 2017; Reynolds  
401      et al. 2020).

402      **A role of neutral drift is unlikely** Differences in organismal traits between environments  
403      are not necessarily proof of adaptation or selection, and genetic drift may result in patterns sim-  
404      ilar to local adaptation (Miles et al., 2019). Nevertheless, two lines of evidence from our data  
405      suggest that this scenario may be implausible. First, we found little evidence for a role of phe-  
406      notypic isolation-by-distance (spatial autocorrelation) in explaining the differences we report. We  
407      did detect a significant signal of isolation-by-distance on Eleuthera, but there were no differences  
408      in dewlap coloration between habitats on this island. Second, we detected differences between  
409      habitats at relatively small spatial scales, most of the time between sites 5-10km apart, sometimes  
410      a few hundred meters away, on Bimini for example. Such small-scale differences would be unlikely  
411      under strong gene flow (Richardson et al., 2014). Our study islands lack geographic barriers to the  
412      movement of *A. sagrei*, which have been shown to be highly mobile (Kamath and Losos, 2018),  
413      implying widespread gene flow across sites and habitats. Moreover, habitat-populations within  
414      each island were found to be non-monophyletic and often share identical haplotypes, based on  
415      phylogenetic analysis of mitochondrial DNA sequences (van de Schoot et al. unpublished thesis),  
416      suggesting gene flow between habitats may be widespread.

417

418      Our results align with previous documented cases of persistent dewlap color divergence despite  
419      gene flow in multiple species of anoles, sometimes in relation to environmental conditions. Ng et al.  
420      (2012) and Ng et al. (2016) found divergent dewlap coloration in the face of gene flow between

subspecies of *A. distichus* across Hispaniola, and proposed this as a mechanism of reproductive isolation in the early stages of speciation (Ng and Glor, 2011; Lambert et al., 2013; Ng et al., 2017). Stapley et al. (2011) found that dewlap color polymorphism was maintained in the absence of genetic structure between populations of *A. apletophallus* from Panama. Thorpe and Stenson (2002) found that divergence in dewlap coloration matched habitat-type better than mitochondrial lineage in *A. roquet* on Martinique, and a convergent pattern was found in *A. trinitatis* on the featureless island of St Vincent (Thorpe, 2002). Finally, regionally-distinct body coloration, but not dewlap coloration, is present in *A. conspersus* on another small island, Grand Cayman, where no physical barriers to gene flow exist (Macedonia, 2001).

421  
422  
423  
424  
425  
426  
427  
428  
429  
430

**Dewlap coloration could be locally adapted** Although phenotypic divergence at small spatial scales may be an indicator of local adaptation, the inconsistency of the between-habitat divergence patterns we observed across islands implies that neutral processes cannot be definitely ruled out (Losos, 2011). Conversely, the absence of parallel divergence across islands does not rule out local adaptation either (Losos, 2011). If selection has an effect, it may be dependent on aspects of the environment that are not encompassed by our broad habitat-type classification into coastal dry scrub, primary coppice forest and mangrove forest, and dewlap coloration may be influenced by a mosaic of interacting local environmental factors, which need not be the same across islands.

431  
432  
433  
434  
435  
436  
437  
438  
439  
440  
441  
442  
443  
444  
445  
446  
447  
448  
449  
450  
451  
452  
453  
454  
455  
456  
457  
458  
459  
460  
461

Previous studies have described convergent patterns of dewlap color evolution in similar environments across islands and species (Thorpe and Stenson, 2002; Thorpe, 2002). Others have suggested that dewlap coloration may have evolved to be maximally detectable under local light conditions imposed by the environment, primarily through UV contrast (i.e. UV-brighter dewlaps in UV-dark, mesic habitats and UV-darker dewlaps in UV-bright, xeric habitats), in *A. cristatellus* and *A. cooki* from Puerto Rico (Leal and Fleishman, 2002, 2004). Although UV reflectance was commonly involved in between-habitat divergence in *A. cooki* and *A. cristatellus*, we found no such patterns in *A. sagrei*, where instead, we found the darkest dewlaps in the dark, mesic habitat – primary coppice forest – on three islands, and dewlaps often differed the most between beach scrub and mangrove forest, two xeric habitats with similar, high irradiance levels (Howard, 1950; Schoener, 1968). The inconsistent and idiosyncratic patterns we observed suggest that dewlap color variation between habitats cannot be predicted by habitat identity alone. Studies of Jamaican and Hispaniolan anoles similarly found between-habitat differences in dewlap coloration but no evidence for higher dewlap detectability in different habitats (Fleishman et al., 2009; Ng et al., 2012). Habitats on different islands may also differ in aspects other than light conditions, such as densities of predators or congeners, which have been shown to affect among-island dewlap diversity (Vanhooydonck et al., 2009; Baeckens et al., 2018). In particular, Baeckens et al. (2018) recently showed that dewlaps with spotted patterns occurred more often in *A. sagrei* on islands with more coexisting species of anoles. Our data are consistent with those previous results in suggesting that adaptation to local light conditions, or at least broad habitat types, may not be a major driver of the within-island variation in dewlap coloration in *A. sagrei*.

**Sexual selection could be at play** Sexual selection is an important component of an adaptive, sensory drive hypothesis of dewlap color divergence across environmental conditions, because in this scenario habitat-dependent selection is executed by the signal recipients (Endler and McLellan, 1988), such as mating partners (Driessens et al., 2014). An alternative yet non-mutually exclusive explanation for the observed idiosyncratic patterns of within-island divergence is that of "Fisherian" sexual selection (Andersson, 1994). Under the Fisherian model of sexual selection, arbitrary female preferences (i.e. independent of the environment) for certain male ornaments may drive divergent evolution of male signals, such as dewlap coloration, if female preferences differ between localities for other reasons than environment-dependent perception abilities (a situation that could have arisen e.g. in an initial phase of genetic drift). Substantial levels of promiscuity in *A. sagrei* suggest ample opportunity for female mate choice (Kamath and Losos, 2018), and are in line with this explanation. Therefore, arbitrary, habitat-independent female preferences could further explain the inconsistent patterns of divergence across islands. In contrast with this, however, Baeckens et al. (2018) found no link between *A. sagrei* dewlap coloration and size dimorphism (a proxy for sexual selection) in an among-island study of the same archipelagos.

462  
463  
464  
465  
466  
467  
468  
469  
470  
471  
472  
473  
474  
475  
476

477      Besides, although this process is well-established in some systems such as African cichlids (e.g.  
478 Seehausen 1997), previous work suggests that dewlap coloration in *Anolis* may act as a mating cue  
479 according to a "good genes" model of sexual selection (Andersson, 1994), rather than a Fisherian  
480 process. In the good genes model, the cue under sexual selection is an indicator of individual  
481 quality (e.g. better immune response to disease) and of indirect benefit to the offspring. For ex-  
482 ample, Cook et al. (2013) found lower orange reflectance in dewlaps with heavily parasitized *A.*  
483 *brevirostris*, suggesting a trade-off in carotenoid use between the immune response and pigment  
484 deposition. Steffen and Guyer (2014) found that lower UV and orange-red reflectance predict  
485 contest-winning success between *A. sagrei* males, while Driessens et al. (2015) further found that  
486 more yellow and red dewlaps (relative to UV) predict better body condition, and that higher yellow  
487 and UV reflectance at the margin of the dewlap predict higher hematocrit (the concentration of  
488 red blood cells), indicating a better health. Other aspects of the dewlap than color have also been  
489 found to be indicators of individual quality, such as dewlap size (Vanhooydonck et al., 2005, 2009),  
490 but not dewlap display frequency (Tokarz, 2002; Tokarz et al., 2005; Driessens et al., 2015).  
491

492

493 **A role of phenotypic plasticity is unlikely** Differences in coloration between habitat popu-  
494 lations may not be genetically determined, and may be influenced by environmental factors such  
495 as parasite load, as mentioned above (Cook et al., 2013). The yellow, orange and red coloration in  
496 anoline dewlaps are produced by pterins and carotenoids (Ortiz, 1962; Ortiz et al., 1962; Ortiz and  
497 Williams-Ashman, 1963; Ortiz and Maldonado, 1966; Macedonia et al., 2000; Steffen and McGraw,  
498 2007, 2009). Animals lack the ability to synthesize carotenoids, and those must therefore be found  
499 in the diet, while pterins are synthesized from nucleotides (Goodwin, 1984; Hill et al., 2002; Hill  
500 and McGraw, 2006). However, experimental manipulation of dietary carotenoid content showed  
501 no effect on dewlap coloration in *A. sagrei* (Steffen et al., 2010) nor in *A. distichus* (Ng et al.,  
502 2013), which also has an orange-based dewlap. This makes a plastic response to differences in  
503 diet across habitats unlikely. Furthermore, developmental plasticity during the ontogeny is also  
504 unlikely because dewlap coloration develops at sexual maturity in anoles (Ng et al., 2013). The  
505 differences we observed could therefore be heritable. This hypothesis is further supported by Cox  
506 et al. (2017), who found a high degree of heritability of dewlap coloration in *A. sagrei*. Although  
507 most studies used one or two-generation common garden experiments and thus could not rule out  
508 transgenerational plastic effects (Tariel et al., 2020), dewlap coloration generally seems to not be a  
509 plastic trait. This further reinforces an adaptive explanation, where dewlap color could be under  
510 differential natural and/or sexual selection in these different habitats.

511

512 **Implications in the context of speciation** Local adaptation can be a precursor to ecological  
513 speciation, a process that may have given rise to the adaptive radiation of *Anolis* lizards (Harmon  
514 et al., 2003; Gavrilets and Losos, 2009). Ecologically-mediated divergence of a sexual signal may  
515 be a potent path to the evolution of reproductive isolation through divergent sexual selection  
516 (Reynolds and Fitzpatrick, 2007; Servedio et al., 2011). Evidence suggests that dewlap coloration  
517 could take this role in anoles (Ng and Glor, 2011; Lambert et al., 2013; Geneva et al., 2015;  
518 Ng et al., 2017), or at least that it is frequently involved in species recognition (Williams, 1969;  
519 Williams and Rand, 1977; Losos, 1985; Macedonia and Stamps, 1994; Fleishman, 2000; Macedonia  
520 et al., 2013; Ingram et al., 2016; Baeckens et al., 2018). Although this signal is not detected at  
521 the phylogenetic scale of the whole genus (Nicholson et al., 2007; Harrison and Poe, 2012; Ingram  
522 et al., 2016), sexual signals are often evolutionarily very labile (Kraaijeveld et al., 2011), and  
523 the anole dewlap in particular is capable of rapid macroevolution; for example, *A. conspersus* on  
524 Grand Cayman evolved a UV-blue dewlap from an ancestral orange dewlap in 2 to 3 million years  
525 (Macedonia, 2001). We present evidence of multiple cases of potentially adaptive maintenance of  
526 habitat-associated dewlap divergence over small geographical scales in *A. sagrei* across the West  
527 Indies. While these intra-island populations do not appear to be in the process of speciation,  
528 our results suggest that the anoline dewlap has enough micro-scale, local adaptive potential to  
529 contribute to reproductive isolation, should it be recruited for assortative mating.

## Acknowledgements

530

Collection permission was granted by the Bahamas Environment, Science and Technology Commission, the Bahamas National Trust, and the Cayman Islands Department of the Environment. The authors thank Sofia Prado-Irwin, Pavitra Muralidhar, Nicholas Herrmann, Richard E. Glor, Alberto R. Puente-Rolón, Kevin Aviles-Rodriguez, Kristin Winchell, Jason Fredette and Melissa Kemp for assistance in the field and Max Lambert and James Stroud for helpful discussions. Funding for this work was provided by the Templeton Foundation (to JBL), NSF DEB #1927194 (to JBL and AJG), NSF DEB #1500761 (to AJG), NSF DBI #1609284 (to CMD), and a Harvard Museum of Comparative Zoology Putnam Expedition Grant (to RGR).

531

532

533

534

535

536

537

538

**539 Figures**

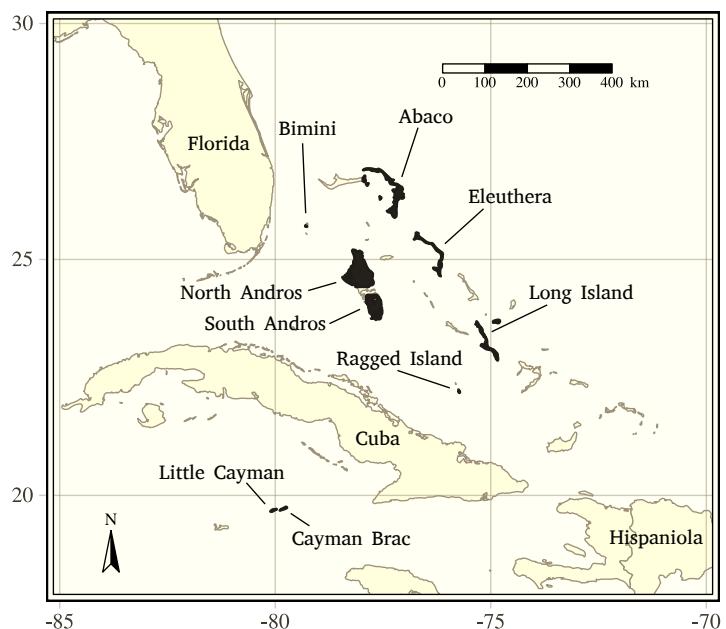


Figure 1: Map of the West Indies with sampled islands highlighted in black.

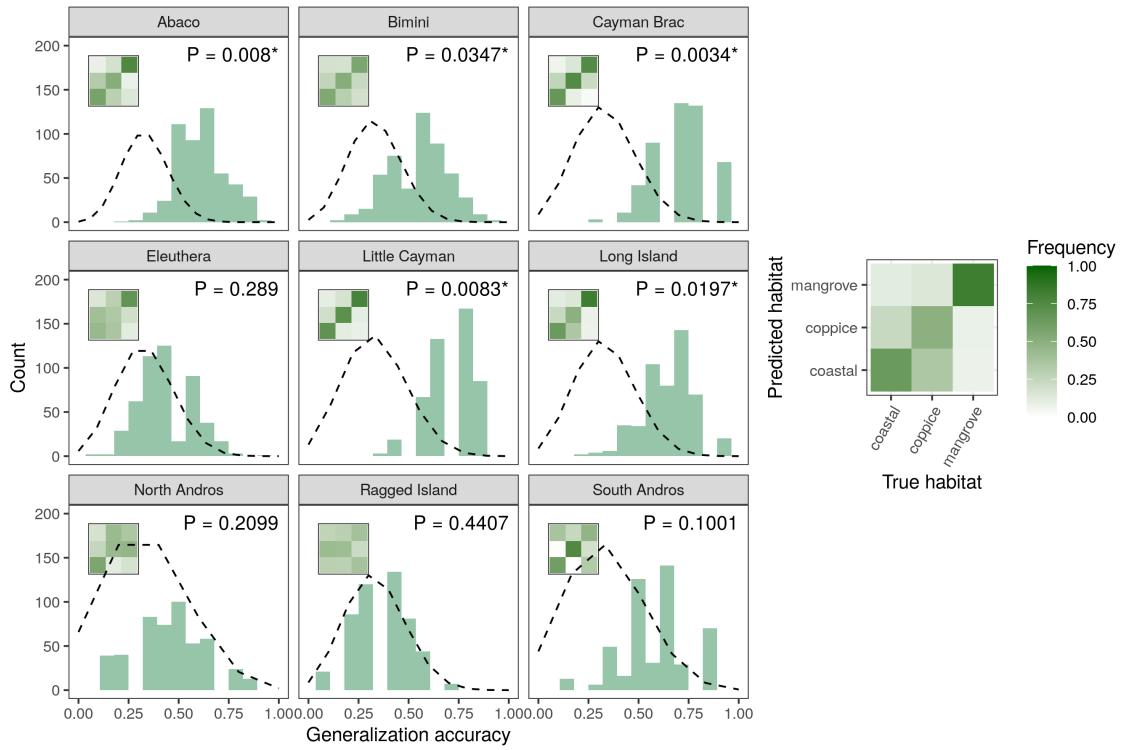


Figure 2: SVM classification accuracy across islands based on principal component data. Histograms show accuracy distributions over 100 replicates for each five cross-validation bins per island. The dashed line is the density of a corresponding null binomial distribution, which would be expected under random guessing (testing sets with 20% of the observations for each island and success probability of 1/3). Inset plots show the corresponding average confusion matrices and represent the proportion of lizards from each habitat (columns) reassigned in each other habitat (rows), with an interpretation guide in the right panel. Binomial test P-values indicate deviations of the mean classification accuracy to the null distribution. \*,  $P < 0.05$ .

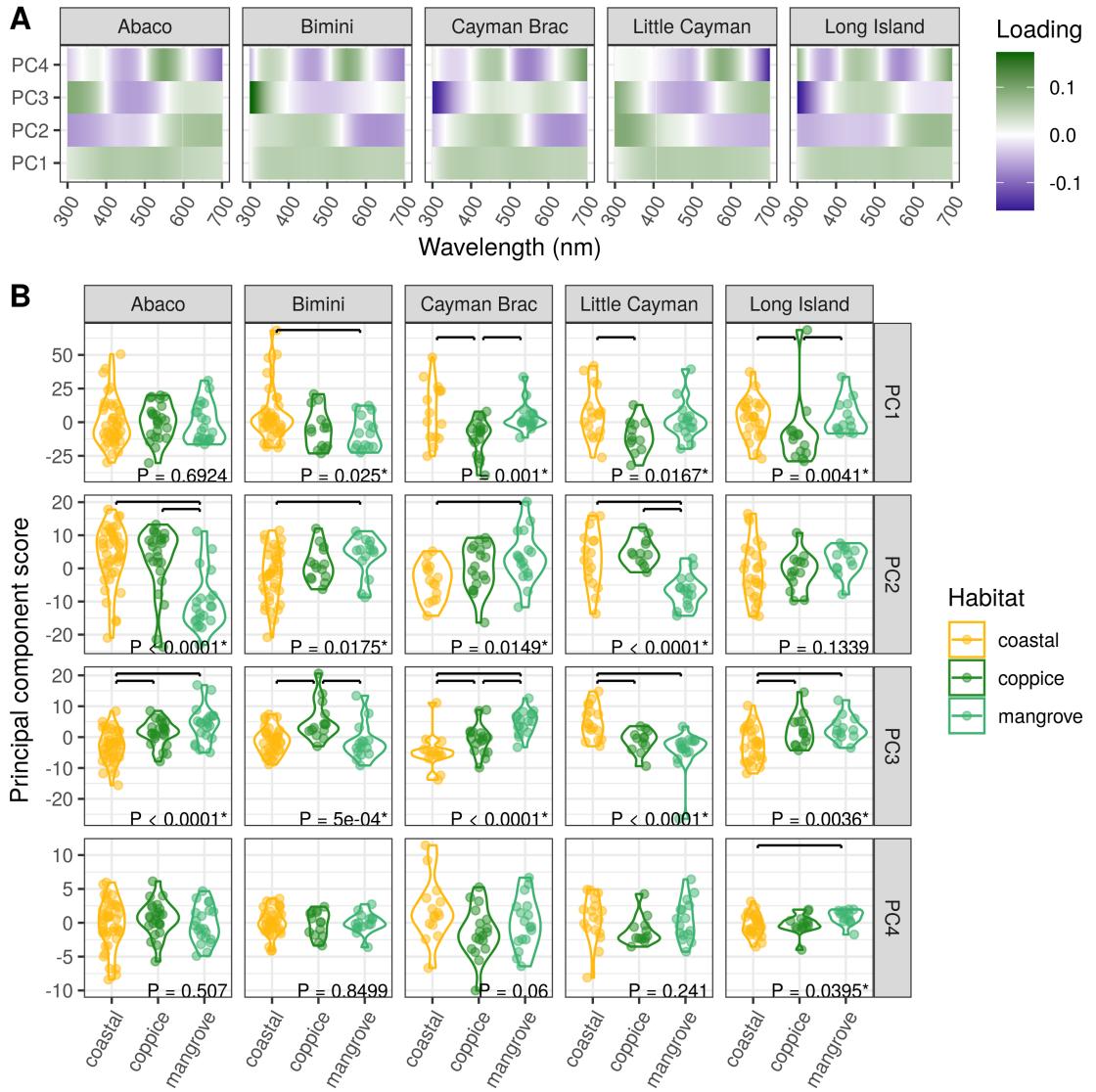


Figure 3: Dewlap color variation between habitat-types across the most significant islands. (A) Mapping of reflectance at various wavelengths onto the principal components (loadings from the PCA rotation matrix). (B) Distribution of PC scores between habitats along the first four PCs on each island where significant between-habitat differences were detected using SVMs. P-values are reported for univariate ANOVA (or Kruskal-Wallis tests when applicable, see Methods). Post hoc significant differences at a 0.05 error rate are indicated with horizontal bars. \*,  $P < 0.05$ .

## Tables

540

Table 1: Significance of habitat differences in dewlap coloration, using ANOVA for all islands where significant multivariate differences in dewlap coloration were detected by SVMs. Best fitting model: 1, OLS; 2, GLS. df, degrees of freedom.  $\Delta \text{AICc}$ , difference in AICc between the best fitting model and the OLS-model. AICcw, AICc weight. LRT, likelihood ratio test. Log-lik., log-likelihood.  $\chi^2$ , likelihood ratio. \*,  $P < 0.05$ ; \*\*,  $P < 0.01$ ; \*\*\*,  $P < 0.001$ .

Island	Variable	Best fit	df	AICc	$\Delta \text{AICc}$	AICcw	$\Delta \text{AICc}$	dfLRT	Log-lik.	$\chi^2$	P
Abaco	PC1	1	4	710.4	0.0	0.746	2	-357.0	0.14	0.9308	***
Abaco	PC2	1	4	620.1	0.0	0.882	2	-310.2	31.74	0.0000	***
Abaco	PC3	1	4	517.8	0.0	0.732	2	-257.2	27.37	0.0000	***
Abaco	PC4	1	4	440.6	0.0	0.596	2	-217.2	1.36	0.5070	*
Bimini	PC1	1	4	561.3	0.0	0.595	2	-283.1	7.40	0.0248	*
Bimini	PC2	1	4	448.1	0.0	0.656	2	-223.8	8.09	0.0175	*
Bimini	PC3	2	6	405.3	-0.2	0.529	2	-199.2	10.39	0.0056	**
Bimini	PC4	1	4	274.2	0.0	0.854	2	-132.7	0.33	0.8499	***
Cayman Brac	PC1	2	6	402.8	-4.1	0.884	2	-200.9	13.81	0.0010	**
Cayman Brac	PC2	1	4	332.1	0.0	0.853	2	-165.9	8.41	0.0149	*
Cayman Brac	PC3	1	4	295.8	0.0	0.800	2	-146.6	27.16	0.0000	***
Cayman Brac	PC4	1	4	279.2	0.0	0.897	2	-137.8	5.63	0.0600	*
Little Cayman	PC1	1	4	367.2	0.0	0.777	2	-186.0	8.18	0.0167	*
Little Cayman	PC2	2	6	287.6	-3.6	0.859	2	-140.5	29.76	0.0000	***
Little Cayman	PC3	1	4	277.7	0.0	0.669	2	-138.1	21.34	0.0000	***
Little Cayman	PC4	1	4	226.7	0.0	0.780	2	-110.7	2.85	0.2410	
Long Island	PC1	2	6	442.3	-2.1	0.740	2	-221.2	2.91	0.2331	
Long Island	PC2	2	6	351.4	-3.1	0.823	2	-172.6	4.52	0.1043	
Long Island	PC3	1	4	322.1	0.0	0.862	2	-160.0	11.24	0.0036	**
Long Island	PC4	1	4	195.5	0.0	0.767	2	-92.9	6.46	0.0395	*

## References

- Andersson, M. B. (1994). *Sexual Selection*. Monographs in Behavior and Ecology. Princeton University Press, Princeton, N.J. 541
- Arnold, S. J. (1983). Morphology, Performance and Fitness. *American Zoologist*, 23(2):347–361. 542
- Baeckens, S., Driessens, T., and Van Damme, R. (2018). The brown anole dewlap revisited: Do predation pressure, sexual selection, and species recognition shape among-population signal diversity? *PeerJ*, 6:e4722. 543
- Bartoń, K. (2019). MuMIn: Multi-Model Inference. 544
- Benjamini, Y. and Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society Series B*, 57:289–300. 545
- Box, G. E. P. (1949). A General Distribution Theory for a Class of Likelihood Criteria. *Biometrika*, 36(3/4):317. 546
- Bradbury, J. W. and Vehrencamp, S. L. (2011). *Principles of Animal Communication*. Sinauer Associates, Sunderland, Mass, 2nd ed edition. 547
- Cook, E. G., Murphy, T. G., and Johnson, M. A. (2013). Colorful displays signal male quality in a tropical anole lizard. *Naturwissenschaften*, 100(10):993–996. 548
- Cortes, C. and Vapnik, V. (1995). Support-vector networks. *Machine Learning*, 20(3):273–297. 549
- Cortez, P. (2010). Data Mining with Neural Networks and Support Vector Machines Using the R/rminer Tool. In Perner, P., editor, *Advances in Data Mining - Applications and Theoretical Aspects 10th Industrial Conference on Data Mining (ICDM 2010), Lecture Notes in Artificial Intelligence 6171*, number 6171 in Lecture Notes in Computer Science Lecture Notes in Artificial Intelligence, pages 572–583. Springer, Berlin. 550
- Cortez, P. (2016). Rminer: Data Mining Classification and Regression Methods. 551
- Cortez, P. and Embrechts, M. J. (2013). Using sensitivity analysis and visualization techniques to open black box data mining models. *Information Sciences*, 225:1–17. 552
- Cox, R. M., Costello, R. A., Camber, B. E., and McGlothlin, J. W. (2017). Multivariate genetic architecture of the *Anolis* dewlap reveals both shared and sex-specific features of a sexually dimorphic ornament. *Journal of Evolutionary Biology*, 30(7):1262–1275. 553
- Cristianini, N. and Shawe-Taylor, J. (2000). *An Introduction to Support Vector Machines and Other Kernel-Based Learning Methods*. Cambridge University Press, first edition. 554
- Cuthill, I. C., Bennett, A. T. D., Partridge, J. C., and Maier, E. J. (1999). Plumage Reflectance and the Objective Assessment of Avian Sexual Dichromatism. *The American Naturalist*, 153(2):183–200. 555
- Dieckmann, U. and Doebeli, M. (1999). On the origin of species by sympatric speciation. *Nature*, 400(6742):354–357. 556
- Driessens, T., Baeckens, S., Balzarolo, M., Vanhooydonck, B., Huyghe, K., and Van Damme, R. (2017). Climate-related environmental variation in a visual signalling device: The male and female dewlap in *Anolis sagrei* lizards. *Journal of Evolutionary Biology*, 30(10):1846–1861. 557
- Driessens, T., Huyghe, K., Vanhooydonck, B., and Van Damme, R. (2015). Messages conveyed by assorted facets of the dewlap, in both sexes of *Anolis sagrei*. *Behavioral Ecology and Sociobiology*, 69(8):1251–1264. 558
- Driessens, T., Vanhooydonck, B., and Van Damme, R. (2014). Deterring predators, daunting opponents or drawing partners? Signaling rates across diverse contexts in the lizard *Anolis sagrei*. *Behavioral Ecology and Sociobiology*, 68(2):173–184. 559

- 586 Dunnett, C. W. (1980). Pairwise Multiple Comparisons in the Unequal Variance Case. *Journal of*  
587 *the American Statistical Association*, 75(372):796–800.
- 588 Endler, J. (1998). Sensory ecology, receiver biases and sexual selection. *Trends in Ecology &*  
589 *Evolution*, 13(10):415–420.
- 590 Endler, J. A. (1984). Natural and sexual selection on color patterns in poeciliid fishes. In Balon,  
591 E. K. and Zaret, T. M., editors, *Evolutionary Ecology of Neotropical Freshwater Fishes*, volume 3,  
592 pages 95–111. Springer Netherlands, Dordrecht.
- 593 Endler, J. A. (1990). On the measurement and classification of colour in studies of animal colour  
594 patterns. *Biological Journal of the Linnean Society*, 41(4):315–352.
- 595 Endler, J. A. (1991). Variation in the appearance of guppy color patterns to guppies and their  
596 predators under different visual conditions. *Vision Research*, 31(3):587–608.
- 597 Endler, J. A. (1992). Signals, Signal Conditions, and the Direction of Evolution. *The American*  
598 *Naturalist*, 139:S125–S153.
- 599 Endler, J. A. (1993a). The Color of Light in Forests and Its Implications. *Ecological Monographs*,  
600 63(1):1–27.
- 601 Endler, J. A. (1993b). Some general comments on the evolution and design of animal communi-  
602 cation systems. *Philosophical Transactions of the Royal Society of London. Series B: Biological*  
603 *Sciences*, 340(1292):215–225.
- 604 Endler, J. A. and McLellan, T. (1988). The Processes of Evolution: Toward a Newer Synthesis.  
605 *Annual Review of Ecology and Systematics*, 19(1):395–421.
- 606 Felsenstein, J. (1976). The Theoretical Population Genetics of Variable Selection and Migration.  
607 *Annual Review of Genetics*, 10(1):253–280.
- 608 Fleishman, L. J. (2000). *Signal Function, Signal Efficiency and the Evolution of Anoline Lizard*  
609 *Dewlap Color*, pages 209–236. Tapir Academic, Trondheim.
- 610 Fleishman, L. J., Leal, M., and Persons, M. H. (2009). Habitat light and dewlap color diversity in  
611 four species of Puerto Rican anoline lizards. *Journal of Comparative Physiology A*, 195(11):1043–  
612 1060.
- 613 Fleishman, L. J. and Persons, M. (2001). The influence of stimulus and background colour on  
614 signal visibility in the lizard *Anolis cristatellus*. *The Journal of Experimental Biology*, 204(Pt  
615 9):1559–1575.
- 616 Fox, J., Friendly, M., and Monette, G. (2018). Heplots: Visualizing Tests in Multivariate Linear  
617 Models.
- 618 Friedrich, S., Konietzschke, F., and Pauly, M. (2018). Analysis of Multivariate Data and Repeated  
619 Measures Designs with the R Package MANOVA.RM. *arXiv:1801.08002 [stat]*.
- 620 García-Ramos, G. and Kirkpatrick, M. (1997). Genetic Models of Adaptation and Gene Flow in  
621 Peripheral Populations. *Evolution*, 51(1):21–28.
- 622 Gavrilets, S. and Losos, J. B. (2009). Adaptive Radiation: Contrasting Theory with Data. *Science*,  
623 323(5915):732–737.
- 624 Geneva, A. J., Hilton, J., Noll, S., and Glor, R. E. (2015). Multilocus phylogenetic analyses of  
625 Hispaniolan and Bahamian trunk anoles (*distichus* species group). *Molecular Phylogenetics and*  
626 *Evolution*, 87:105–117.
- 627 Gittleman, J. L. and Kot, M. (1990). Adaptation: Statistics and a Null Model for Estimating  
628 Phylogenetic Effects. *Systematic Zoology*, 39(3):227.
- 629 Goodwin, T. W. (1984). *The Biochemistry of the Carotenoids*. Springer Netherlands, Dordrecht.
- 630 Halfwerk, W., Jones, P. L., Taylor, R. C., Ryan, M. J., and Page, R. A. (2014). Risky Ripples Allow  
631 Bats and Frogs to Eavesdrop on a Multisensory Sexual Display. *Science*, 343(6169):413–416.

Harmon, L. J., Schulte, J. A., Larson, A., and Losos, J. B. (2003). Tempo and Mode of Evolutionary Radiation in Iguanian Lizards. <i>Science</i> , 301(5635):961–964.	632 633
Harrison, A. and Poe, S. (2012). Evolution of an ornament, the dewlap, in females of the lizard genus <i>Anolis</i> . <i>Biological Journal of the Linnean Society</i> , 106(1):191–201.	634 635
Hendry, A. P., Day, T., and Taylor, E. B. (2007a). Population Mixing and the Adaptive Divergence of Quantitative Traits in Discrete Populations: A Theoretical Framework for Empirical Tests. <i>Evolution</i> , 55(3):459–466.	636 637 638
Hendry, A. P., Taylor, E. B., and McPhail, J. D. (2007b). Adaptive Divergence and the Balance Between Selection and Gene Flow: Lake and Stream Stickleback in the Misty System. <i>Evolution</i> , 56(6):1199–1216.	639 640 641
Henze, N. and Zirkler, B. (1990). A class of invariant consistent tests for multivariate normality. <i>Communications in Statistics - Theory and Methods</i> , 19(10):3595–3617.	642 643
Hijmans, R. J. (2019). Geosphere: Spherical Trigonometry.	644
Hill, G. E., Inouye, C. Y., and Montgomerie, R. (2002). Dietary carotenoids predict plumage coloration in wild house finches. <i>Proceedings of the Royal Society of London. Series B: Biological Sciences</i> , 269(1496):1119–1124.	645 646 647
Hill, G. E. and McGraw, K. J., editors (2006). <i>Bird Coloration</i> . Harvard University Press, Cambridge, Mass.	648 649
Hollander, M., Wolfe, D. A., and Chicken, E. (2013). <i>Nonparametric Statistical Methods</i> . Wiley Series in Probability and Statistics. John Wiley & Sons, Inc, Hoboken, New Jersey, third edition edition.	650 651 652
Howard, R. A. (1950). Vegetation of the Bimini Island Group: Bahamas, B. W. I. <i>Ecological Monographs</i> , 20(4):317–349.	653 654
Ingram, T., Harrison, A., Mahler, D. L., Castañeda, M. d. R., Glor, R. E., Herrel, A., Stuart, Y. E., and Losos, J. B. (2016). Comparative tests of the role of dewlap size in <i>Anolis</i> lizard speciation. <i>Proceedings of the Royal Society B: Biological Sciences</i> , 283(1845):20162199.	655 656 657
Kamath, A. and Losos, J. B. (2018). Estimating encounter rates as the first step of sexual selection in the lizard <i>Anolis sagrei</i> . <i>Proceedings of the Royal Society B: Biological Sciences</i> , 285(1873):20172244.	658 659 660
Kim, B. and von Oertzen, T. (2018). Classifiers as a model-free group comparison test. <i>Behavior Research Methods</i> , 50(1):416–426.	661 662
Colbe, J. J., Larson, A., Losos, J. B., and de Queiroz, K. (2008). Admixture determines genetic diversity and population differentiation in the biological invasion of a lizard species. <i>Biology Letters</i> , 4(4):434–437.	663 664 665
Kolbe, J. J., Leal, M., Schoener, T. W., Spiller, D. A., and Losos, J. B. (2012). Founder Effects Persist Despite Adaptive Differentiation: A Field Experiment with Lizards. <i>Science</i> , 335(6072):1086–1089.	666 667 668
Korkmaz, S., Goksuluk, D., and Zararsiz, G. (2014). MVN: An R Package for Assessing Multivariate Normality. <i>The R Journal</i> , 6(2):151–162.	669 670
Kraaijeveld, K., Kraaijeveld-Smit, F. J. L., and Maan, M. E. (2011). Sexual selection and speciation: The comparative evidence revisited. <i>Biological Reviews</i> , 86(2):367–377.	671 672
Lambert, S. M., Geneva, A. J., Luke Mahler, D., and Glor, R. E. (2013). Using genomic data to revisit an early example of reproductive character displacement in Haitian <i>Anolis</i> lizards. <i>Molecular Ecology</i> , 22(15):3981–3995.	673 674 675
Lazareva, O. F., Shimizu, T., and Wasserman, E. A. (2012). <i>How Animals See the World Comparative Behavior, Biology, and Evolution of Vision</i> . Oxford University Press.	676 677

- 678 Leal, M. and Fleishman, L. J. (2002). Evidence for habitat partitioning based on adaptation to  
679 environmental light in a pair of sympatric lizard species. *Proceedings of the Royal Society of*  
680 *London. Series B: Biological Sciences*, 269(1489):351–359.
- 681 Leal, M. and Fleishman, L. J. (2004). Differences in Visual Signal Design and Detectability between  
682 Allopatric Populations of *Anolis* Lizards. *The American Naturalist*, 163(1):26–39.
- 683 Leal, M. and Rodríguez-Robles, J. A. (1995). Antipredator Responses of *Anolis cristatellus* (Sauria:  
684 Polychrotidae). *Copeia*, 1995(1):155–161.
- 685 Leal, M. and Rodriguez-Robles, J. A. (1997). Antipredator Responses of the Puerto Rican Giant  
686 Anole, *Anolis cuvieri* (Squamata: Polychrotidae). *Biotropica*, 29(3):372–375.
- 687 Leal, M. and Rodríguez-Robles, J. A. (1997). Signalling displays during predator-prey interactions  
688 in a Puerto Rican anole, *Anolis cristatellus*. *Animal Behaviour*, 54(5):1147–1154.
- 689 Lenormand, T. (2002). Gene flow and the limits to natural selection. *Trends in Ecology & Evolution*,  
690 17(4):183–189.
- 691 Losos, J. B. (1985). An Experimental Demonstration of the Species-Recognition Role of *Anolis*  
692 Dewlap Color. *Copeia*, 1985(4):905–910.
- 693 Losos, J. B. (2009). *Lizards in an Evolutionary Tree: Ecology and Adaptive Radiation of Anoles*.  
694 University of California Press.
- 695 Losos, J. B. (2011). Convergence, Adaptation, and Constraint. *Evolution*, 65(7):1827–1840.
- 696 Losos, J. B., Irschick, D. J., and Schoener, T. W. (1994). Adaptation and Constraint in the  
697 Evolution of Specialization of Bahamian *Anolis* Lizards. *Evolution*, 48(6):1786–1798.
- 698 Losos, J. B., Schoener, T. W., Warheit, K. I., and Creer, D. (2001). Experimental studies of  
699 adaptive differentiation in Bahamian *Anolis* lizards. *Genetica*, 112–113:399–415.
- 700 Losos, J. B., Warheit, K. I., and Schoener, T. W. (1997). Adaptive differentiation following  
701 experimental island colonization in *Anolis* lizards. *Nature*, 387(6628):70–73.
- 702 Macedonia, J. M. (2001). Habitat light, colour variation, and ultraviolet reflectance in the Grand  
703 Cayman anole, *Anolis conspersus*. *Biological Journal of the Linnean Society*, 73(3):299–320.
- 704 Macedonia, J. M., Clark, D. L., Riley, R. G., and Kemp, D. J. (2013). Species recognition of color  
705 and motion signals in *Anolis grahami*: Evidence from responses to lizard robots. *Behavioral*  
706 *Ecology*, 24(4):846–852.
- 707 Macedonia, J. M., Clark, D. L., and Tamasi, A. L. (2014). Does Selection Favor Dewlap Colors that  
708 Maximize Detectability? A Test with Five Species of Jamaican *Anolis* Lizards. *Herpetologica*,  
709 70(2):157–170.
- 710 Macedonia, J. M., James, S., Wittle, L. W., and Clark, D. L. (2000). Skin Pigments and Coloration  
711 in the Jamaican Radiation of *Anolis* Lizards. *Journal of Herpetology*, 34(1):99–109.
- 712 Macedonia, J. M. and Stamps, J. A. (1994). Species Recognition in *Anolis grahami* (Sauria,  
713 Iguanidae): Evidence from Responses to Video Playbacks of Conspecific and Heterospecific  
714 Displays. *Ethology*, 98(3-4):246–264.
- 715 Maia, R., Eliason, C. M., Bitton, P.-P., Doucet, S. M., and Shawkey, M. D. (2013). Pavo: An  
716 R package for the analysis, visualization and organization of spectral data. *Methods in Ecology*  
717 and *Evolution*, pages n/a–n/a.
- 718 Miles, L. S., Rivkin, L. R., Johnson, M. T. J., Munshi-South, J., and Verrelli, B. C. (2019). Gene  
719 flow and genetic drift in urban environments. *Molecular Ecology*, 28(18):4138–4151.
- 720 Morrison, D. F. (1988). *Multivariate Statistical Methods*. McGraw-Hill Series in Probability and  
721 Statistics. McGraw-Hill, Hamburg Auckland.
- 722 Nemenyi, P. (1963). *Distribution-Free Multiple Comparisons*. Ph. D. dissertation, Princeton Uni-  
723 versity, Princeton, NJ.

Ng, J., Geneva, A. J., Noll, S., and Glor, R. E. (2017). Signals and Speciation: <i>Anolis</i> Dewlap Color as a Reproductive Barrier. <i>Journal of Herpetology</i> , 51(3):437–447.	724 725
Ng, J. and Glor, R. E. (2011). Genetic differentiation among populations of a Hispaniolan trunk anole that exhibit geographical variation in dewlap colour. <i>Molecular Ecology</i> , 20(20):4302–4317.	726 727
Ng, J., Kelly, A. L., MacGuigan, D. J., and Glor, R. E. (2013). The Role of Heritable and Dietary Factors in the Sexual Signal of a Hispaniolan <i>Anolis</i> Lizard, <i>Anolis distichus</i> . <i>Journal of Heredity</i> , 104(6):862–873.	728 729 730
Ng, J., Landeen, E. L., Logsdon, R. M., and Glor, R. E. (2012). Correlation Between <i>Anolis</i> Lizard Dewlap Phenotype and Environmental Variation Indicates Adaptive Divergence of a Signal Important to Sexual Selection and Species Recognition. <i>Evolution</i> , 67(2):573–582.	731 732 733
Ng, J., Ossip-Klein, A. G., and Glor, R. E. (2016). Adaptive signal coloration maintained in the face of gene flow in a Hispaniolan <i>Anolis</i> Lizard. <i>BMC Evolutionary Biology</i> , 16(1):193.	734 735
Nicholson, K. E., Harmon, L. J., and Losos, J. B. (2007). Evolution of <i>Anolis</i> Lizard Dewlap Diversity. <i>PLoS ONE</i> , 2(3):e274.	736 737
Nosil, P. and Crespi, B. J. (2004). Does Gene Flow Constrain Adaptive Divergence or Vice Versa? A Test Using Ecomorphology and Sexual Isolation in <i>Timema cristinae</i> Walking-Sticks. <i>Evolution</i> , 58(1):102–112.	738 739 740
Ortiz, E. (1962). Drosopterins in the dewlap of some anoline lizards. <i>American Zoologist</i> , 2:545–546.	741
Ortiz, E. and Maldonado, A. A. (1966). Pteridine accumulation in lizards of the genus <i>Anolis</i> . <i>Caribbean Journal of Science</i> , 6:9–13.	742 743
Ortiz, E., Throckmorton, L. H., and Williams-Ashman, H. G. (1962). Drosopterins in the Throat-Fans of Some Puerto Rican Lizards. <i>Nature</i> , 196(4854):595–596.	744 745
Ortiz, E. and Williams-Ashman, H. (1963). Identification of skin pteridines in the pasture lizard <i>Anolis pulchellus</i> . <i>Comparative Biochemistry and Physiology</i> , 10(3):181–190.	746 747
Pigot, A. L., Sheard, C., Miller, E. T., Bregman, T. P., Freeman, B. G., Roll, U., Seddon, N., Trisos, C. H., Weeks, B. C., and Tobias, J. A. (2020). Macroevolutionary convergence connects morphological form to ecological function in birds. <i>Nature Ecology &amp; Evolution</i> , 4(2):230–239.	748 749 750
Pinheiro, J. and Bates, D. (2000). <i>Mixed-Effects Models in S and S-PLUS</i> . Statistics and Computing. Springer-Verlag, New York.	751 752
Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., and Team, R. C. (2020). <i>Nlme: Linear and Nonlinear Mixed Effects Models</i> .	753 754
Pohlert, T. (2020). PMCMRplus: Calculate Pairwise Multiple Comparisons of Mean Rank Sums Extended. R package version 1.4.4.	755 756
R Core Team (2019). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing.	757 758
Rand, A. S. and Williams, E. E. (1970). An Estimation of Redundancy and Information Content of Anole Dewlaps. <i>The American Naturalist</i> , 104(935):99–103.	759 760
Reynolds, R. G. and Fitzpatrick, B. M. (2007). Assortative Mating in Poison-Dart Frogs Based on an Ecologically Important Trait. <i>Evolution</i> , 61(9):2253–2259.	761 762
Reynolds, R. G., Kolbe, J. J., Glor, R. E., López-Darias, M., Gómez Pourroy, C. V., Harrison, A. S., Queiroz, K., Revell, L. J., and Losos, J. B. (2020). Phylogeographic and phenotypic outcomes of brown anole colonization across the Caribbean provide insight into the beginning stages of an adaptive radiation. <i>Journal of Evolutionary Biology</i> , 33(4):468–494.	763 764 765 766
Richardson, J. L. and Urban, M. C. (2013). Strong Selection Barriers Explain Microgeographic Adaptation in Wild Salamander Populations. <i>Evolution</i> , 67(6):1729–1740.	767 768

- 769 Richardson, J. L., Urban, M. C., Bolnick, D. I., and Skelly, D. K. (2014). Microgeographic adap-  
770 tation and the spatial scale of evolution. *Trends in Ecology & Evolution*, 29(3):165–176.
- 771 Ripley, B. D. (1996). *Pattern Recognition and Neural Networks*. Cambridge University Press, first  
772 edition.
- 773 Schoener, T. W. (1968). The *Anolis*Lizards of Bimini: Resource Partitioning in a Complex Fauna.  
774 *Ecology*, 49(4):704–726.
- 775 Seehausen, O. (1997). Cichlid Fish Diversity Threatened by Eutrophication That Curbs Sexual  
776 Selection. *Science*, 277(5333):1808–1811.
- 777 Servedio, M. R., Doorn, G. S. V., Kopp, M., Frame, A. M., and Nosil, P. (2011). Magic traits in  
778 speciation: ‘magic’ but not rare? *Trends in Ecology & Evolution*, 26(8):389–397.
- 779 Sigmund, W. R. (1983). Female Preference for *Anolis carolinensis* Males as a Function of Dewlap  
780 Color and Background Coloration. *Journal of Herpetology*, 17(2):137–143.
- 781 Stapley, J., Wordley, C., and Slate, J. (2011). No Evidence of Genetic Differentiation Between  
782 Anoles With Different Dewlap Color Patterns. *Journal of Heredity*, 102(1):118–124.
- 783 Steffen, J. E. and Guyer, C. C. (2014). Display behaviour and dewlap colour as predictors of  
784 contest success in brown anoles: Dewlap Colour and Behaviour in Contests. *Biological Journal of the Linnean Society*, 111(3):646–655.
- 785 Steffen, J. E., Hill, G. E., and Guyer, C. (2010). Carotenoid Access, Nutritional Stress, and the  
786 Dewlap Color of Male Brown Anoles. *Copeia*, 2010(2):239–246.
- 787 Steffen, J. E. and McGraw, K. J. (2007). Contributions of pterin and carotenoid pigments to dewlap  
788 coloration in two anole species. *Comparative Biochemistry and Physiology Part B: Biochemistry  
789 and Molecular Biology*, 146(1):42–46.
- 790 Steffen, J. E. and McGraw, K. J. (2009). How dewlap color reflects its carotenoid and pterin content  
791 in male and female brown anoles (*Norops sagrei*). *Comparative Biochemistry and Physiology Part B: Biochemistry  
792 and Molecular Biology*, 154(3):334–340.
- 793 Tariel, J., Plénet, S., and Luquet, É. (2020). Transgenerational plasticity of inducible defences:  
794 Combined effects of grand-parental, parental and current environments. *Ecology and Evolution*,  
795 10(5):2367–2376.
- 796 Thorpe, R. S. (2002). Analysis of Color Spectra in Comparative Evolutionary Studies: Molecular  
797 Phylogeny and Habitat Adaptation in the St. Vincent Anole (*Anolis trinitatis*). *Systematic  
798 Biology*, 51(4):554–569.
- 799 Thorpe, R. S. and Stenson, A. G. (2002). Phylogeny, Paraphyly and Ecological Adaptation of  
800 the Colour and Pattern in the Anolis Roquet Complex on Martinique: Interaction Between  
801 Phylogeny and Adaptation. *Molecular Ecology*, 12(1):117–132.
- 802 Tokarz, R. R. (2002). An Experimental Test of the Importance of the Dewlap in Male Mating  
803 Success in the Lizard *Anolis sagrei*. *Herpetologica*, 58(1):87–94.
- 804 Tokarz, R. R. (2006). Importance of Prior Physical Contact with Familiar Females in the Devel-  
805 opment of a Male Courtship and Mating Preference for Unfamiliar Females in the Lizard *Anolis  
806 Sagrei*. *Herpetologica*, 62(2):115–124.
- 807 Tokarz, R. R., Paterson, A. V., and McMann, S. (2005). Importance of Dewlap Display in  
808 Male Mating Success in Free-Ranging Brown Anoles (*Anolis sagrei*). *Journal of Herpetology*,  
809 39(1):174–177.
- 810 Tukey, J. W. (1949). Comparing Individual Means in the Analysis of Variance. *Biometrics*, 5(2):99.
- 811 Vanhooydonck, B., Herrel, A., Meyers, J. J., and Irschick, D. J. (2009). What determines dewlap  
812 diversity in *Anolis* lizards? An among-island comparison. *Journal of Evolutionary Biology*,  
813 22(2):293–305.

- Vanhooydonck, B., Herrel, A. Y., Van Damme, R., and Irschick, D. J. (2005). Does dewlap size predict male bite performance in Jamaican *Anolis* lizards? *Functional Ecology*, 19(1):38–42. 815  
816
- Venables, W. N. and Ripley, B. D. (2002). *Modern Applied Statistics with S*. Statistics and Computing. Springer, New York, 4th ed edition. 817  
818
- Willi, Y. and Hoffmann, A. A. (2012). Microgeographic adaptation linked to forest fragmentation and habitat quality in the tropical fruit fly *Drosophila birchii*. *Oikos*, 121(10):1627–1637. 819  
820
- Williams, E. E. (1969). The Ecology of Colonization as Seen in the Zoogeography of Anoline Lizards on Small Islands. *The Quarterly Review of Biology*, 44(4):345–389. 821  
822
- Williams, E. E. and Rand, A. S. (1977). Species Recognition, Dewlap Function and Faunal Size. *American Zoologist*, 17(1):261–270. 823  
824
- Zuur, A. F., editor (2009). *Mixed Effects Models and Extensions in Ecology with R*. Statistics for Biology and Health. Springer, New York, NY. 825  
826

<sup>827</sup> **Supplementary Figures**

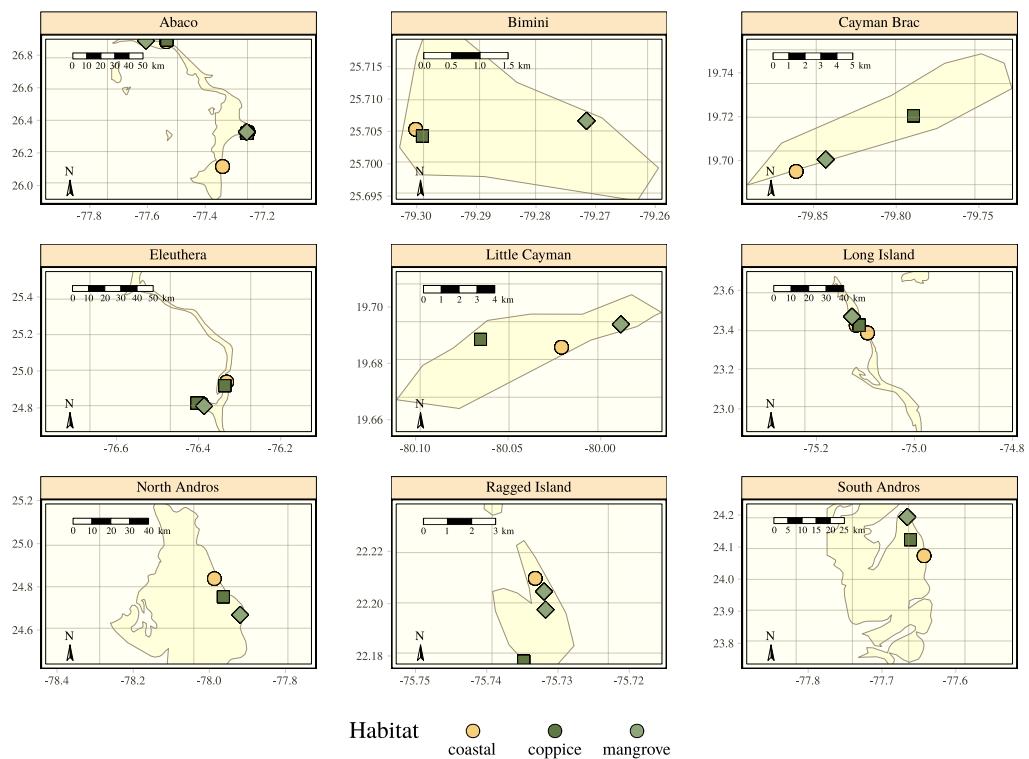


Figure S1: Map of the sampling sites and corresponding habitats across nine islands of the West Indies.

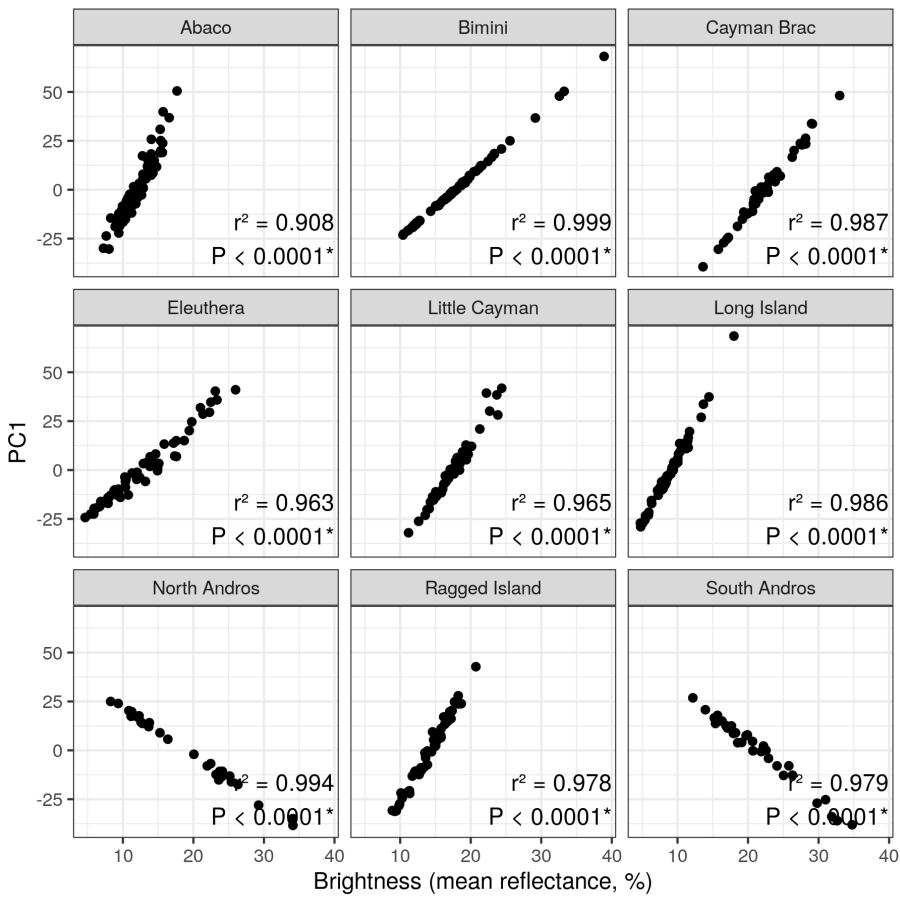


Figure S2: Correlation between dewlap brightness (as measured by the mean reflectance from 300 to 700nm in wavelength) and PC1 score for each island. Pearson's squared correlation coefficients are reported. \*,  $P < 0.05$ .

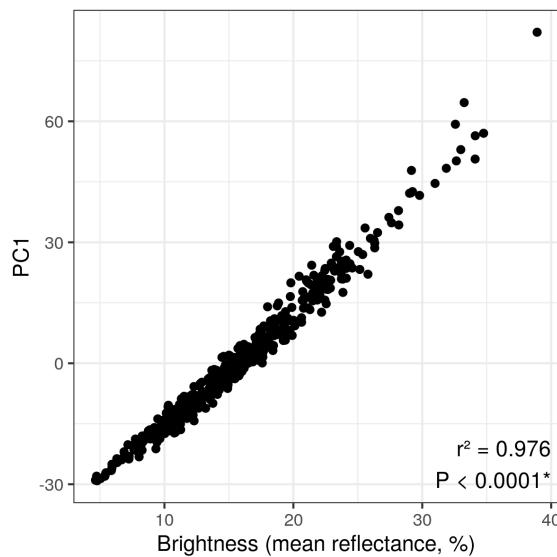


Figure S3: Correlation between dewlap brightness (as measured by the mean reflectance from 300 to 700nm in wavelength) and PC1 score across the whole archipelago. Pearson's squared correlation coefficient is reported. \*,  $P < 0.05$ .

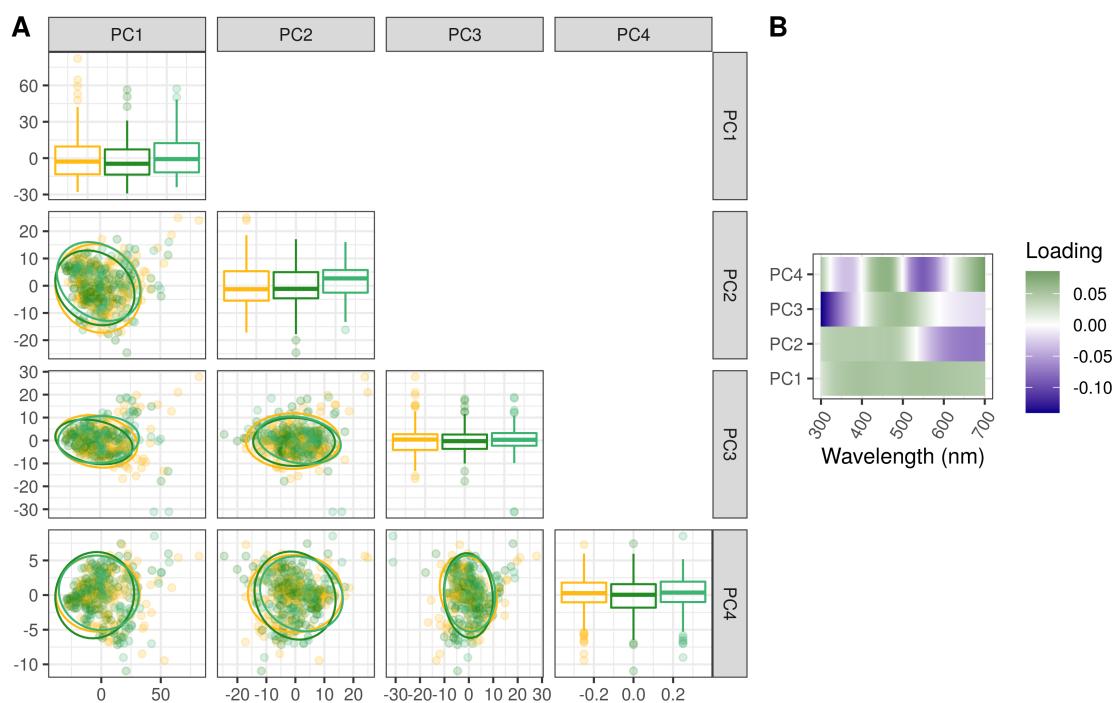


Figure S4: (A) Principal component scores and 5% confidence ellipses across habitats for the whole archipelago. The principal component analysis was performed on reflectance data from all islands pooled together. (B) PCA rotation matrix showing the loadings of each wavelength from 300 to 700nm onto the principal components.

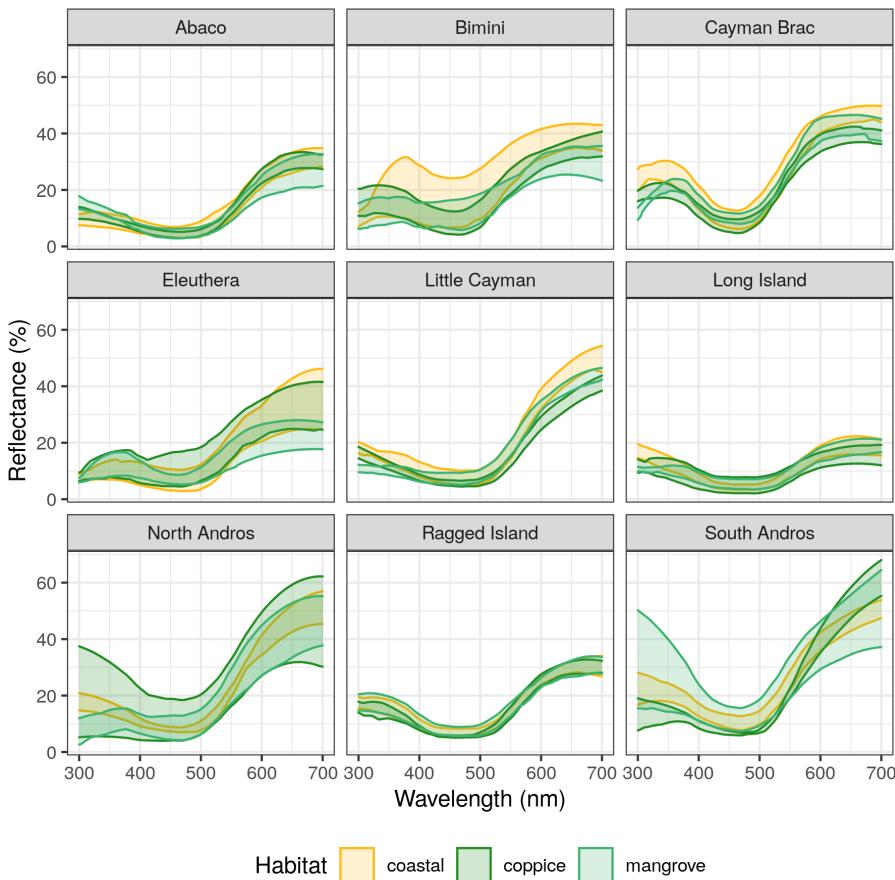


Figure S5: 5-95th percentile range of lizard dewlap reflectance values (in % of incoming light) across wavelengths for each island and each habitat.

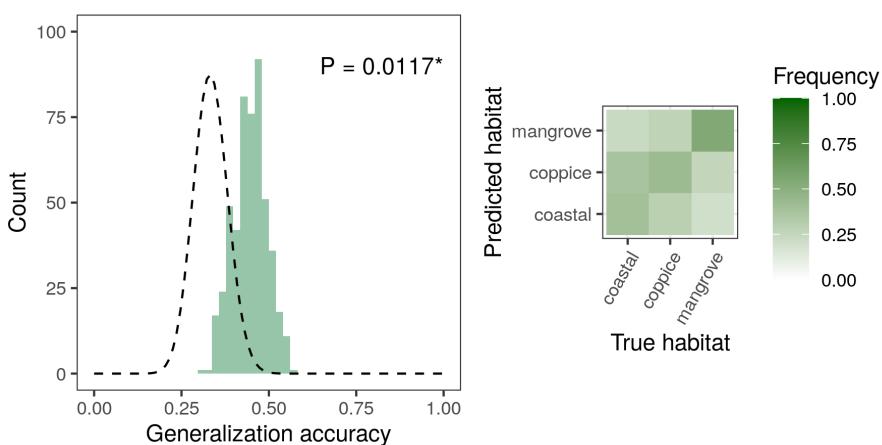


Figure S6: Archipelago-wide SVM classification accuracy based on principal component data. Machines were trained on individual dewlaps regardless of island identity. The histogram shows the accuracy distribution over 100 replicates for each five cross-validation bins. The legend is the same as in Figure 2.

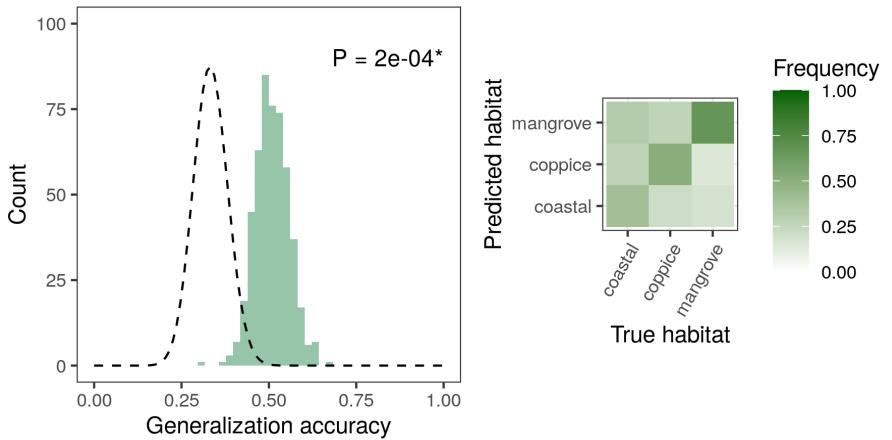


Figure S7: Archipelago-wide SVM classification accuracy based on reflectance data at 50nm-intervals in wavelength (see Methods). Machines were trained on individual dewlaps regardless of island identity. The histogram shows the accuracy distribution over 100 replicates for each five cross-validation bins. The legend is the same as in Figure 2.

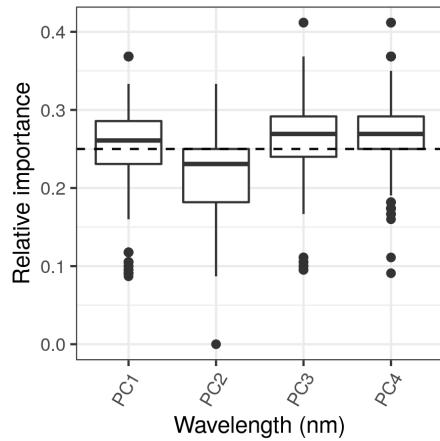


Figure S8: Sensitivity analyses of the different input variables in the archipelago-wide SVM classification on principal component data (Figure S6), with relative importance computed for every machine.

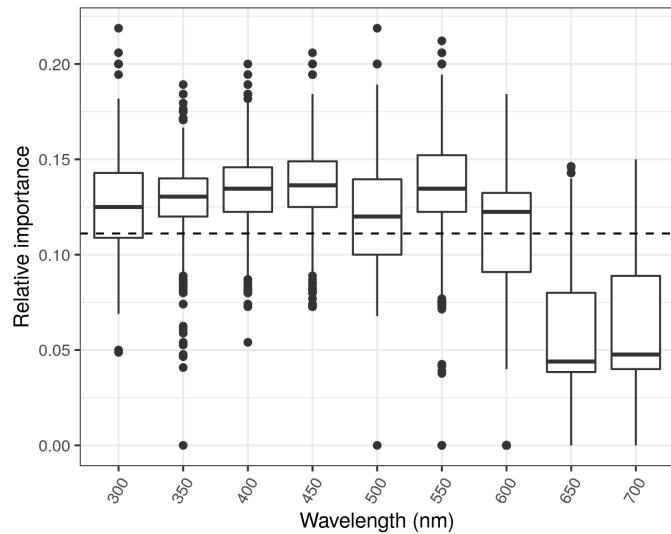


Figure S9: Sensitivity analyses of the different input variables in the archipelago-wide SVM classification on reflectance data at 50nm-intervals in wavelength (Figure S7), with relative importance computed for every machine.

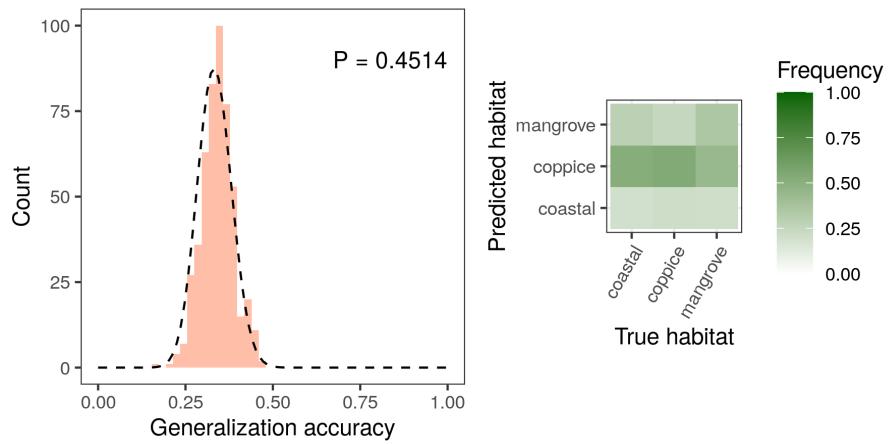


Figure S10: Archipelago-wide LDA classification accuracy based on principal component data. Machines were trained on individual dewlaps regardless of island identity. The histogram shows the accuracy distribution over 100 replicates for each five cross-validation bins. The legend is the same as in Figure 2.

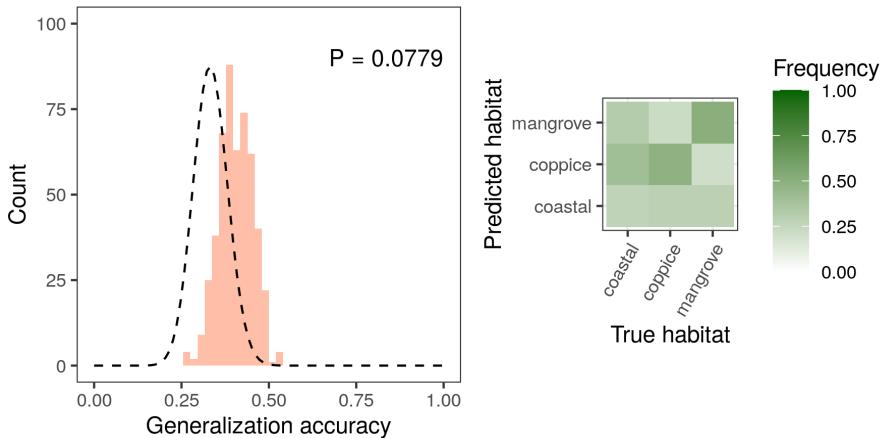


Figure S11: Archipelago-wide LDA classification accuracy based on reflectance data at 5nm intervals in wavelength (see Methods). Machines were trained on individual dewlaps regardless of island identity. The histogram shows the accuracy distribution over 100 replicates for each five cross-validation bins. The legend is the same as in Figure 2.

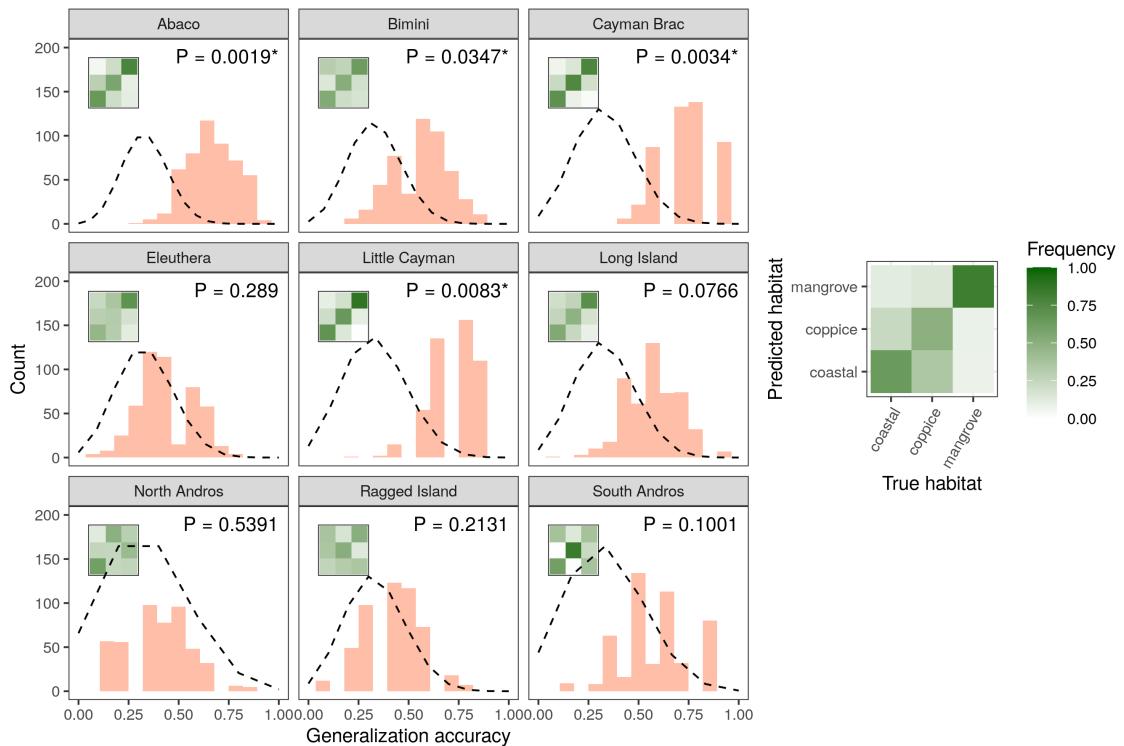


Figure S12: LDA classification accuracy across islands based on principal component data. Histograms show accuracy distributions over 100 replicates for each five cross-validation bins per island. The legend is the same as in Figure 2.

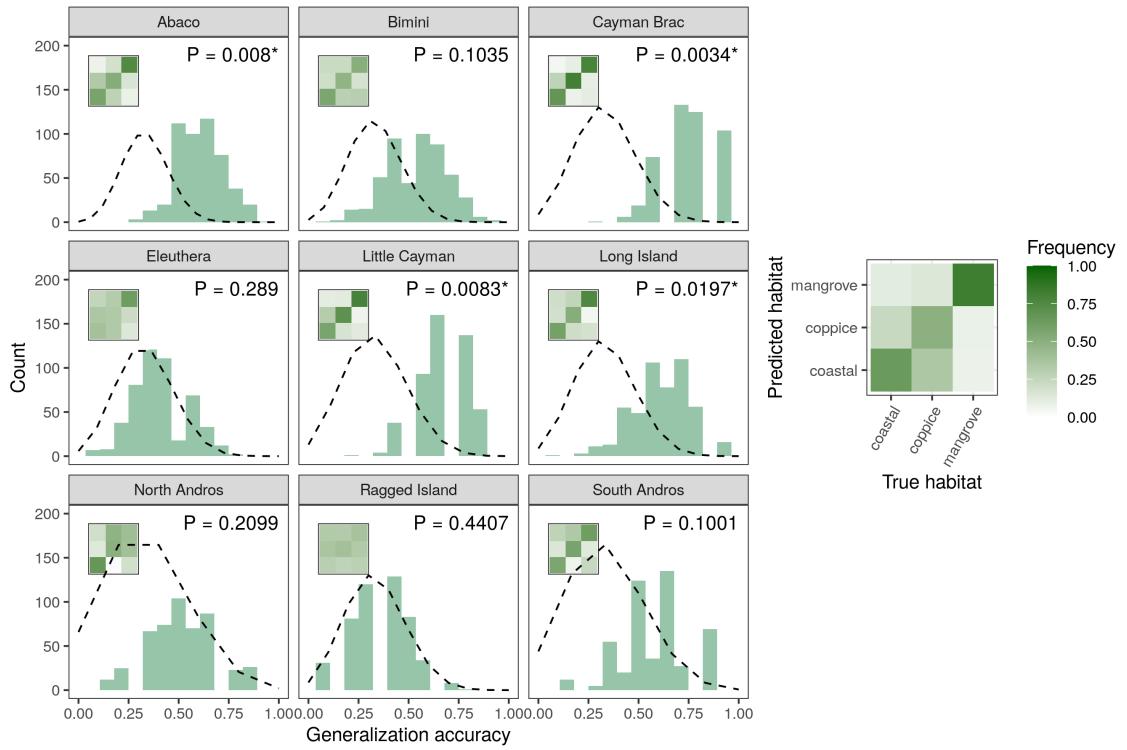


Figure S13: SVM classification accuracy across islands based on reflectance data at 50nm-intervals in wavelength (see Methods). Histograms show accuracy distributions over 100 replicates for each five cross-validation bins per island. The legend is the same as in Figure 2.

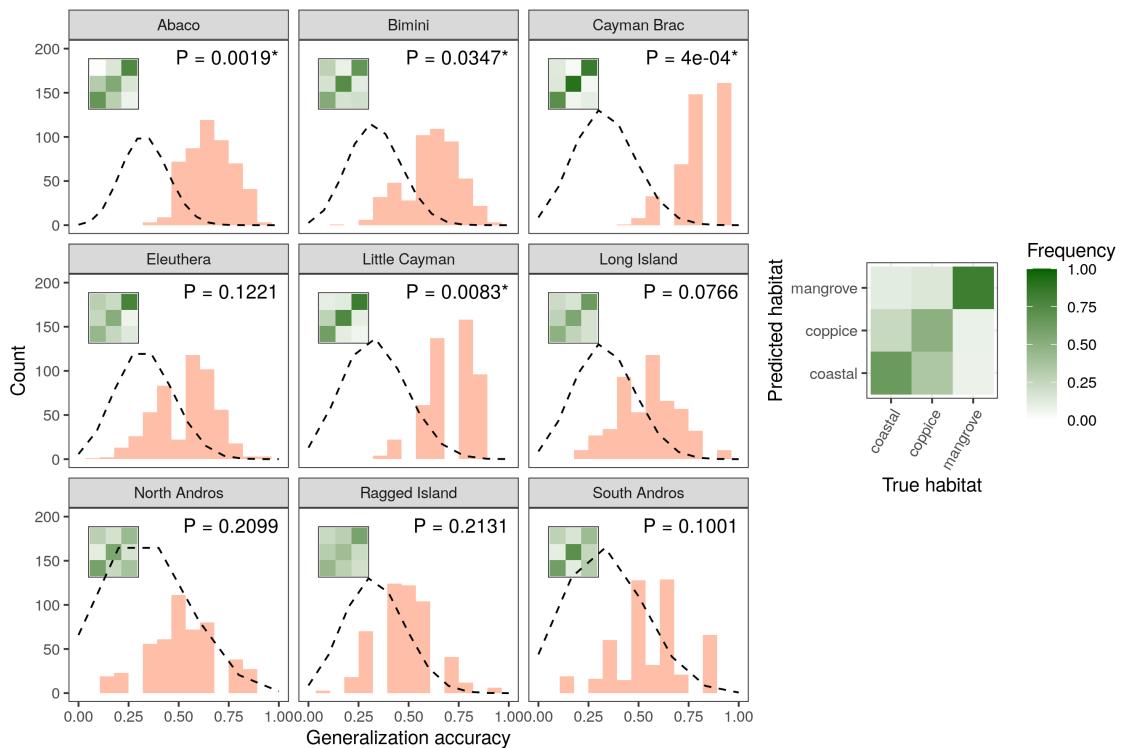


Figure S14: LDA classification accuracy across islands based on reflectance data at 50nm-intervals in wavelength (see Methods). Histograms show accuracy distributions over 100 replicates for each five cross-validation bins per island. The legend is the same as in Figure 2.

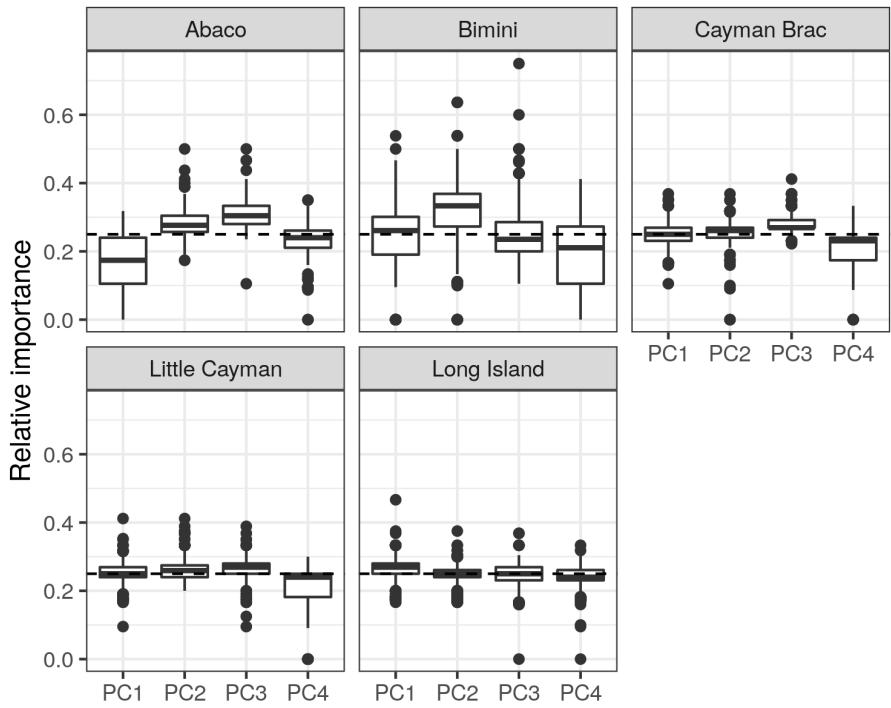


Figure S15: Sensitivity analyses of the different input variables in the within-island SVM classification on principal component data (Figure ??), with relative importance computed for every machine.

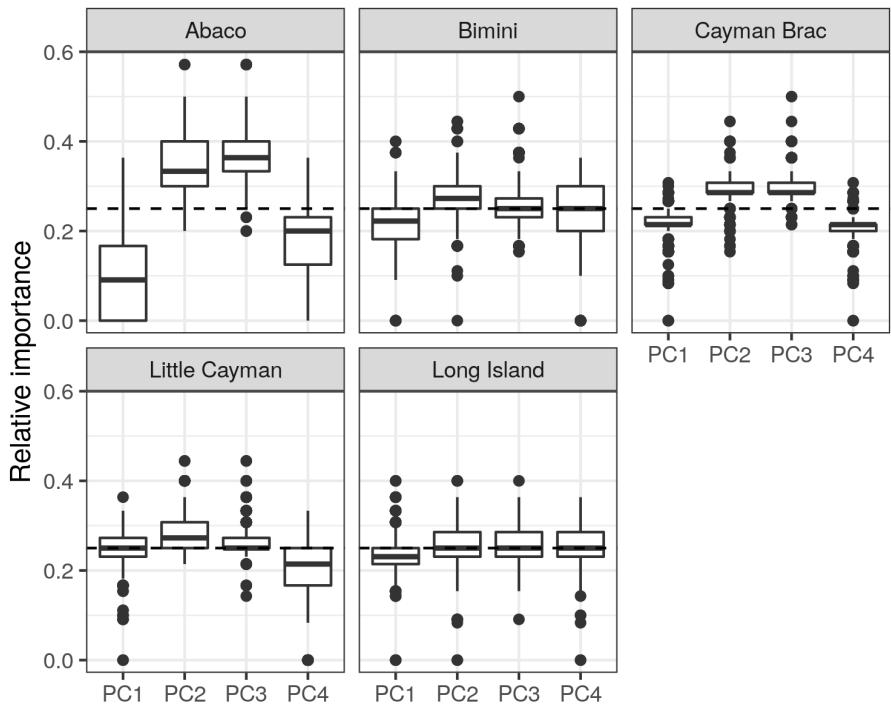


Figure S16: Sensitivity analyses of the different input variables in the within-island LDA classification on principal component data (Figure S12), with relative importance computed for every machine.

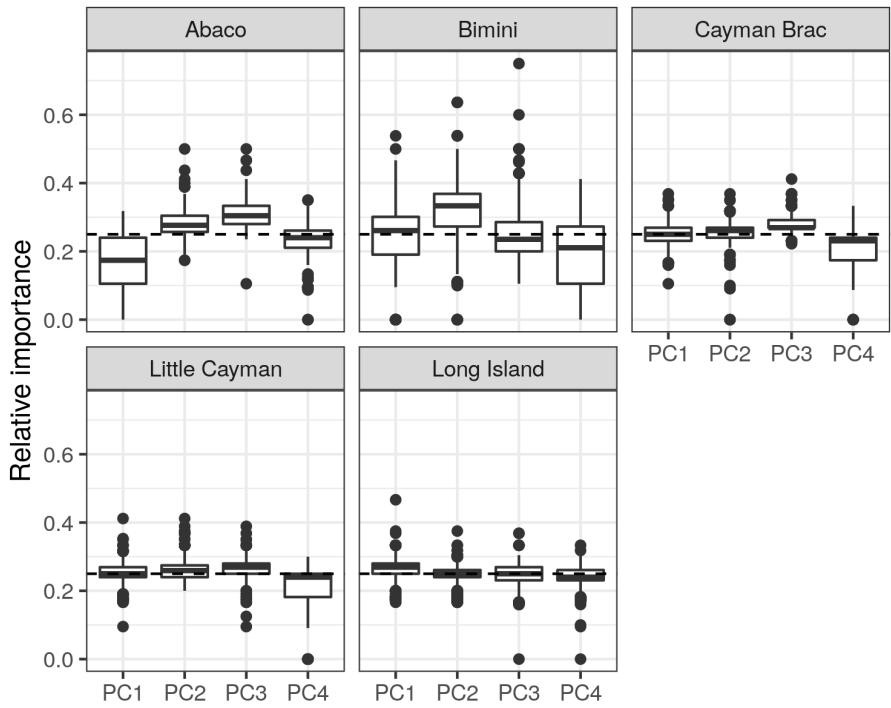


Figure S17: Sensitivity analyses of the different input variables in the archipelago-wide SVM classification on reflectance at 50nm-intervals in wavelength (Figure S13), with relative importance computed for every machine.

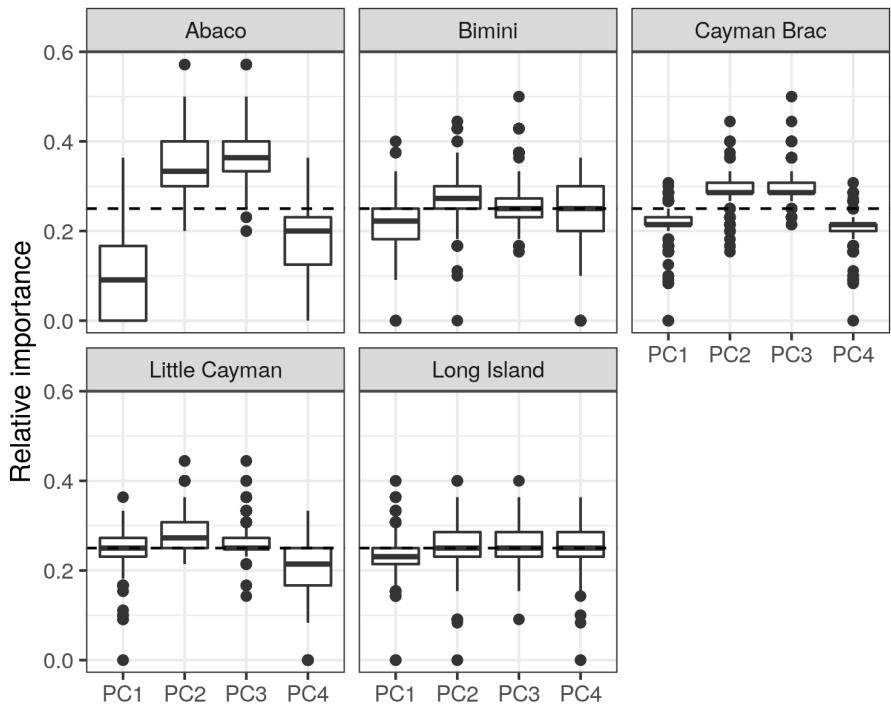


Figure S18: Sensitivity analyses of the different input variables in the archipelago-wide LDA classification on reflectance at 50nm-intervals in wavelength (Figure S14), with relative importance computed for every machine.

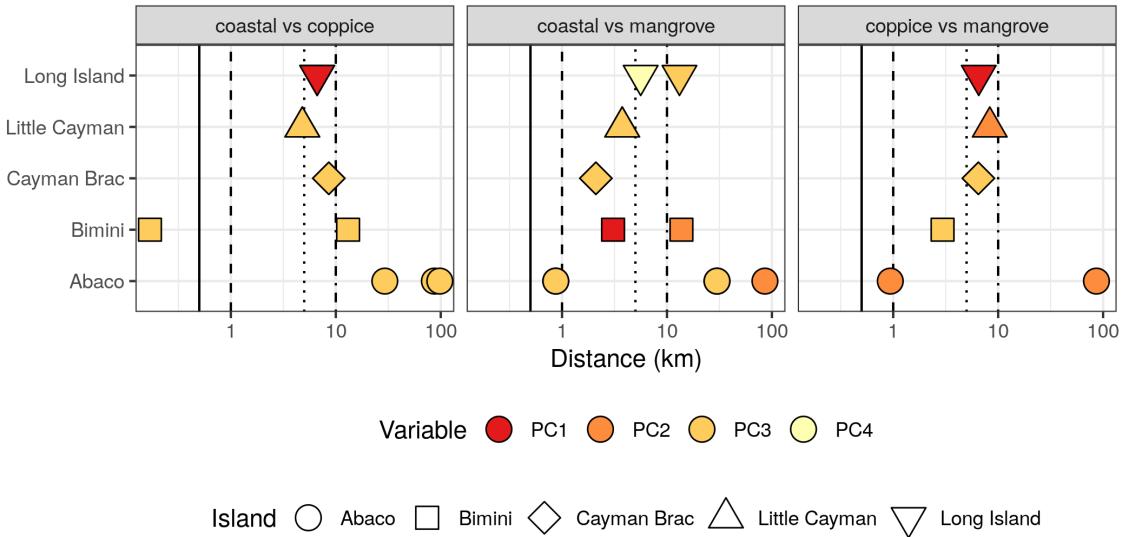


Figure S19: Spatial scale of between-habitat differences in dewlap coloration. For each variable and each pair of habitats where significant differences were detected (Figure 3), we performed multiple post hoc pairwise comparisons between the sites involved (Figure S1, Table S2), using nonparametric Wilcoxon-Mann-Whitney tests. Here we report, for each pair of habitats, the distances between sites that significantly differed in dewlap coloration at an error rate of 0.05 (P-values corrected with the Benjamini-Hochberg procedure for multiple testing).

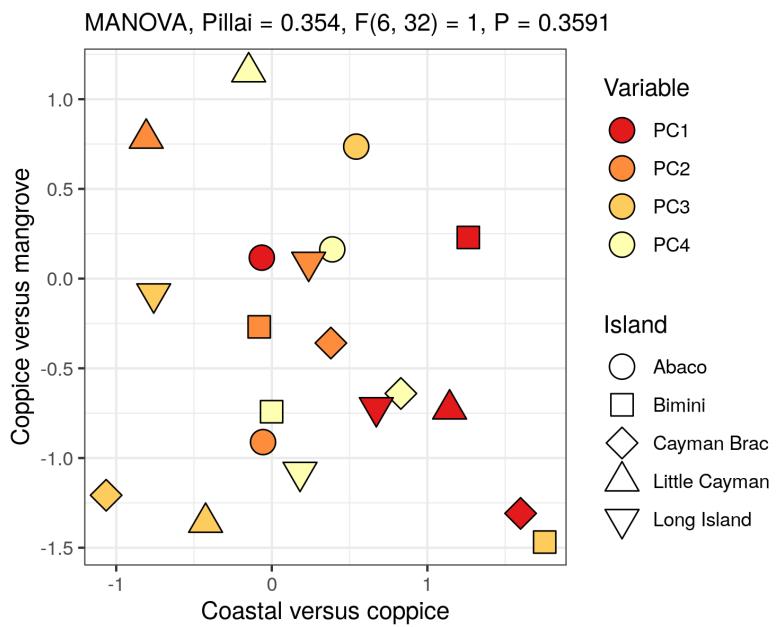


Figure S20: Test of parallel divergence between islands. Differences in habitat-means, or contrasts, are shown for two pairs of habitats for each principal component on each island, rescaled so the standard deviation of the means along each principal component is one. The contrasts represent the patterns of between-habitat variation on each island, for a given principal component. The absence of clustering of islands by variable indicates that islands differ in their between-habitat divergence patterns. This is confirmed by a non-significant MANOVA test of the between versus within-variable variance in contrasts.

## Supplementary Tables

828

Table S1: Number of lizards sampled in each habitat on each island.

	coastal	coppice	mangrove
Abaco	41	24	21
Bimini	38	14	15
Cayman Brac	15	18	17
Eleuthera	22	25	9
Little Cayman	17	12	16
Long Island	26	14	13
North Andros	9	9	10
Ragged Island	18	15	17
South Andros	10	9	12

Table S2: Locations of the sampling sites across islands, with mean principal component scores per site.

Island	Longitude	Latitude	Habitat	PC1	PC2	PC3	PC4
Abaco	-77.7256	26.9083	mangrove	-5.4905	1.3541	-0.4741	0.0083
Abaco	-77.5800	26.9020	coastal	1.8633	0.0365	-0.4475	0.0033
Abaco	-77.5763	26.9128	coppice	-1.6738	-1.7793	-0.0499	0.0012
Abaco	-77.1784	26.1045	coastal	1.1863	2.0408	-0.3468	0.0022
Abaco	-77.0055	26.3254	mangrove	-9.0319	-2.7460	0.4687	0.0077
Abaco	-77.0039	26.3170	coppice	0.9967	0.5161	-0.0267	-0.0118
Abaco	-76.9968	26.3260	coastal	7.6077	0.3186	0.1771	-0.0008
Bimini	-79.3022	25.5859	coastal	5.7537	-0.1593	-0.2505	0.0001
Bimini	-79.3014	25.7052	coastal	-3.1822	1.6617	-0.0460	0.0024
Bimini	-79.3002	25.7042	coppice	-1.3514	-3.8786	0.1027	-0.0027
Bimini	-79.2709	25.7066	mangrove	3.3656	0.6244	0.1569	-0.0021
Cayman Brac	-79.8627	19.6878	coastal	6.6606	-2.5670	0.0166	-0.0007
Cayman Brac	-79.8441	19.6949	mangrove	-1.0914	4.3607	0.0855	0.0001
Cayman Brac	-79.7887	19.7209	coppice	-4.5197	-1.9793	-0.0946	0.0004
Eleuthera	-76.3347	24.8146	coppice	3.2669	-1.2404	0.1018	-0.0085
Eleuthera	-76.3058	24.8127	coastal	0.4216	-3.5133	-0.0567	0.0009
Eleuthera	-76.2901	24.7981	mangrove	2.1881	0.7517	0.3957	-0.0055
Eleuthera	-76.1616	24.9129	coppice	-1.9136	1.0868	-0.4978	-0.0092
Eleuthera	-76.1492	24.9335	coastal	-3.1863	2.4270	0.1881	0.0218
Little Cayman	-80.0660	19.6906	coppice	0.8021	-1.9569	-0.0760	-0.0068
Little Cayman	-80.0205	19.6865	coastal	-6.6917	-1.2615	0.0659	0.0057
Little Cayman	-79.9871	19.6986	mangrove	6.5083	2.8079	-0.0129	-0.0010
Long Island	-75.2299	23.4740	mangrove	-1.2873	1.9371	-0.1880	-0.0029
Long Island	-75.2063	23.4282	coastal	2.3686	-0.9033	0.0215	0.0096
Long Island	-75.1884	23.4292	coppice	-4.6266	0.5060	0.1049	-0.0070
Long Island	-75.1408	23.3883	coastal	3.6139	-1.4521	0.0475	0.0025
North Andros	-77.8908	24.8391	coastal	-2.1881	-1.1236	0.0397	-0.0060
North Andros	-77.8428	24.7516	coppice	-1.8115	0.0012	-0.1678	0.0024
North Andros	-77.7540	24.6644	mangrove	3.5997	1.0101	0.1153	0.0033
Ragged Island	-75.7364	22.1768	coppice	3.2851	-0.3274	0.1911	-0.0013
Ragged Island	-75.7314	22.2097	coastal	-0.6412	-0.8878	-0.1293	-0.0033
Ragged Island	-75.7276	22.2045	mangrove	-2.9188	1.5792	-0.0034	0.0099
Ragged Island	-75.7270	22.1973	mangrove	-1.2210	0.7285	-0.0721	-0.0028
South Andros	-77.6050	24.2027	mangrove	-3.9253	0.4734	0.0477	-0.0005
South Andros	-77.5936	24.1289	coppice	6.1152	-0.4925	0.0349	0.0012
South Andros	-77.5453	24.0764	coastal	-0.7933	-0.1248	-0.0887	-0.0004

Table S3: Proportion of variance explained by the first four principal components on each island, as well as across the whole archipelago.

Island	PC1	PC2	PC3	PC4	Total
Abaco	0.400	0.279	0.147	0.079	0.906
Bimini	0.502	0.208	0.160	0.051	0.921
Cayman Brac	0.438	0.190	0.155	0.105	0.888
Eleuthera	0.490	0.233	0.138	0.066	0.926
Little Cayman	0.441	0.212	0.176	0.078	0.907
Long Island	0.515	0.205	0.161	0.043	0.925
North Andros	0.560	0.170	0.152	0.054	0.937
Ragged Island	0.483	0.226	0.127	0.072	0.907
South Andros	0.488	0.247	0.146	0.067	0.948
Archipelago	0.473	0.197	0.164	0.079	0.913

Table S4: Pearson's correlation test between dewlap brightness, as measured by the average reflectance between 300 and 700nm in wavelength, and PC1 scores, for all islands and across the whole archipelago. \*\*\*,  $P < 0.001$ .

Island	$r^2$	$P$	
Abaco	0.908	< 0.0001	***
Bimini	0.999	< 0.0001	***
Cayman Brac	0.987	< 0.0001	***
Eleuthera	0.963	< 0.0001	***
Little Cayman	0.965	< 0.0001	***
Long Island	0.986	< 0.0001	***
North Andros	0.994	< 0.0001	***
Ragged Island	0.978	< 0.0001	***
South Andros	0.979	< 0.0001	***
Archipelago	0.976	< 0.0001	***

Table S5: Henze-Zirkler's test of multivariate normality, performed on principal components in each habitat and on each island. HZ, test statistic. \*, P < 0.05; \*\*, P < 0.01; \*\*\*, P < 0.001.

Island	Habitat	HZ	P	
Abaco	coastal	1.10	0.0027	**
Abaco	coppice	1.07	0.0022	**
Abaco	mangrove	1.06	0.0023	**
Bimini	coastal	1.28	0.0001	***
Bimini	coppice	0.85	0.0482	*
Bimini	mangrove	1.19	0.0001	***
Cayman Brac	coastal	0.65	0.5311	
Cayman Brac	coppice	0.70	0.3940	
Cayman Brac	mangrove	0.66	0.5357	
Eleuthera	coastal	1.61	0.0000	***
Eleuthera	coppice	1.48	0.0000	***
Eleuthera	mangrove	0.73	0.1423	
Little Cayman	coastal	0.62	0.6599	
Little Cayman	coppice	0.64	0.4867	
Little Cayman	mangrove	0.87	0.0413	*
Long Island	coastal	0.82	0.1468	
Long Island	coppice	0.92	0.0150	*
Long Island	mangrove	0.77	0.1289	
North Andros	coastal	0.66	0.3174	
North Andros	coppice	0.76	0.0900	
North Andros	mangrove	0.67	0.3185	
Ragged Island	coastal	0.76	0.2268	
Ragged Island	coppice	0.80	0.1115	
Ragged Island	mangrove	0.54	0.9022	
South Andros	coastal	0.66	0.3451	
South Andros	coppice	0.66	0.3154	
South Andros	mangrove	0.91	0.0144	*

Table S6: Box's M-test of homogeneity of covariance matrices across habitats on each island.  $\chi^2$ , test statistic. \*, P < 0.05; \*\*, P < 0.01; \*\*\*, P < 0.001.

Island	$\chi^2$	df	P	
Abaco	47.1	20	0.0006	***
Bimini	36.0	20	0.0152	*
Cayman Brac	36.9	20	0.0120	*
Eleuthera	44.6	20	0.0013	**
Little Cayman	32.8	20	0.0356	*
Long Island	56.2	20	0.0000	***
North Andros	33.7	20	0.0283	*
Ragged Island	29.3	20	0.0824	
South Andros	46.5	20	0.0007	***

Table S7: Shapiro-Wilk's test of univariate normality performed on each island where significant differences were detected by SVM classification, in each habitat where deviations from multivariate normality were detected.  $W$ , test statistic. \*,  $P < 0.05$ ; \*\*,  $P < 0.01$ ; \*\*\*,  $P < 0.001$ .

Island	Habitat	Variable	$W$	$P$
Abaco	coastal	PC1	0.954	0.0941
Abaco	coastal	PC2	0.927	0.0112 *
Abaco	coastal	PC3	0.973	0.4228
Abaco	coastal	PC4	0.955	0.1027
Abaco	coppice	PC1	0.970	0.6776
Abaco	coppice	PC2	0.816	0.0005 ***
Abaco	coppice	PC3	0.930	0.0976
Abaco	coppice	PC4	0.941	0.1711
Abaco	mangrove	PC1	0.881	0.0155 *
Abaco	mangrove	PC2	0.869	0.0093 **
Abaco	mangrove	PC3	0.986	0.9873
Abaco	mangrove	PC4	0.939	0.2044
Bimini	coastal	PC1	0.821	0.0000 ***
Bimini	coastal	PC2	0.960	0.1854
Bimini	coastal	PC3	0.856	0.0002 ***
Bimini	coastal	PC4	0.945	0.0611
Bimini	coppice	PC1	0.911	0.1648
Bimini	coppice	PC2	0.958	0.6927
Bimini	coppice	PC3	0.953	0.6146
Bimini	coppice	PC4	0.971	0.8953
Bimini	mangrove	PC1	0.884	0.0536
Bimini	mangrove	PC2	0.976	0.9363
Bimini	mangrove	PC3	0.982	0.9805
Bimini	mangrove	PC4	0.975	0.9232
Eleuthera	coastal	PC1	0.909	0.0461 *
Eleuthera	coastal	PC2	0.886	0.0157 *
Eleuthera	coastal	PC3	0.906	0.0390 *
Eleuthera	coastal	PC4	0.962	0.5293
Eleuthera	coppice	PC1	0.922	0.0567
Eleuthera	coppice	PC2	0.954	0.3055
Eleuthera	coppice	PC3	0.781	0.0001 ***
Eleuthera	coppice	PC4	0.901	0.0188 *
Little Cayman	mangrove	PC1	0.907	0.1024
Little Cayman	mangrove	PC2	0.904	0.0924
Little Cayman	mangrove	PC3	0.739	0.0005 ***
Little Cayman	mangrove	PC4	0.973	0.8802
Long Island	coppice	PC1	0.686	0.0003 ***
Long Island	coppice	PC2	0.848	0.0210 *
Long Island	coppice	PC3	0.931	0.3188
Long Island	coppice	PC4	0.904	0.1280
South Andros	mangrove	PC1	0.787	0.0067 **
South Andros	mangrove	PC2	0.861	0.0500 *
South Andros	mangrove	PC3	0.697	0.0008 ***
South Andros	mangrove	PC4	0.950	0.6411

Table S8: Univariate ANOVAs performed on each principal component across the whole archipelago. Legend is the same as for Table 1, except that best fitting models 3 and 4 refer to the mixed effect equivalents to the OLS and GLS model, with island as a random effect (see Methods).

Variable	Best fit	df	AICc	$\Delta\text{AICc}$	AICcw	$\text{df}_{\text{LRT}}$	Log-lik.	$\chi^2$	P
PC1	3	5	3749.9	-228.3	0.613	2	-1874.7	8.69	0.0130 *
PC2	4	7	3002.2	-162.3	0.976	2	-1496.2	17.76	0.0001 ***
PC3	4	7	2826.3	-175.4	0.968	2	-1407.8	7.03	0.0298 *
PC4	4	7	2015.7	-305.8	0.519	2	-1000.1	0.47	0.7914

Table S9: Mean SVM classification accuracy per island, over all replicates and cross-validation bins.  $N$ , number of observations per island;  $p_{\text{test}}$ , proportion of the data sampled to form the training set;  $n_{\text{test}}$ , number of observations in the testing set. P-values indicate deviations from the expected null binomial distribution, with  $n_{\text{test}}$  events per island and random guess success probability 1/3. \*,  $P < 0.05$ , \*\*,  $P < 0.01$ , \*\*\*,  $P < 0.001$ .

Island	Accuracy	$N$	$p_{\text{test}}$	$n_{\text{test}}$	P
Abaco	0.612	86	0.2	17	0.0080 **
Bimini	0.547	67	0.2	13	0.0347 *
Cayman Brac	0.721	50	0.2	10	0.0034 **
Eleuthera	0.437	56	0.2	11	0.2890
Little Cayman	0.734	45	0.2	9	0.0083 **
Long Island	0.651	53	0.2	10	0.0197 *
North Andros	0.453	28	0.2	5	0.2099
Ragged Island	0.364	50	0.2	10	0.4407
South Andros	0.600	31	0.2	6	0.1001

Table S10: Results of nonparametric Kruskal-Wallis tests performed on each variable on each island where deviations from normality were detected.

Island	Variable	$\chi^2$	df	P
Abaco	PC1	0.74	2	0.6924
Abaco	PC2	23.13	2	0.0000 ***
Bimini	PC1	7.38	2	0.0250 *
Bimini	PC3	15.17	2	0.0005 ***
Little Cayman	PC3	19.95	2	0.0000 ***
Long Island	PC1	10.98	2	0.0041 **
Long Island	PC2	4.02	2	0.1339

Table S11: Individual-based permutation tests of spatial autocorrelation within islands. P-values were computed from 1,000 permutations of individual site-labels. Pearson's coefficient  $r$  measures the correlation between distances in color space and geodesic distances among the sites.  $N$ , number of sites. \*,  $P < 0.05$ .

Island	$r$	$P$	$N$
Abaco	-0.213	0.817	7
Bimini	0.044	0.510	4
Cayman Brac	-0.010	0.465	3
Eleuthera	0.816	0.015	5 *
Little Cayman	-0.688	0.684	3
Long Island	-0.189	0.579	4
North Andros	0.730	0.199	3
Ragged Island	0.706	0.114	4
South Andros	-0.852	0.776	3