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Population Size and Dynamics of the Lima Leaf-Toed Gecko, *Phyllodactylus sentosus*, in One of Its Last Refuges

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Abstract.—The Peruvian endemic Lima Leaf-Toed Gecko (*Phyllodactylus sentosus*) is a critically endangered species with just a few known localities of occurrence, which are isolated from each other, within Lima City and in the Ica region. During 1 yr, we carried out monthly evaluations to determine the influence of the environmental factors on the size and population dynamics of this species in the Huaca Pucllana, as this area maintains one of the largest populations in Lima. We took body measurements and reproductive data and made a total of 1,924 captures and recaptures. The low catchability during the coldest months caused a population underestimation in which adults fluctuated between 69 and 313 and juveniles between 88 and 351 throughout the year for the study area of 6.07 ha. The catchability increased in the warmest months when the adult population peaked between December and January, whereas the population of juveniles peaked in December and April. We noted sexual dimorphism, the females being 8% longer than males. The reproductive cycle seems more similar to that of other species that inhabit the temperate zones, where females have oviductal eggs in spring and the appearance of young individuals occurs in mid- to late summer when food is abundant. We recommend carrying out one evaluation per year in Huaca Pucllana and in the other localities of occurrence of these geckos during summertime. We also recommend carrying out a management program including the translocation of individuals between Huaca Pucllana and the other four closest localities.

Resumen.—Los geckos de Lima (*Phyllodactylus sentosus*) son una especie endémica del Perú y en peligro crítico de extinción, se les ha registrado en un bajo número de localidades de ocurrencia, aisladas entre sí, en la ciudad de Lima y en la región Ica. Realizamos evaluaciones mensuales para determinar la influencia de los factores ambientales en el tamaño y la dinámica poblacional de esta especie en la Huaca Pucllana a lo largo de un año, ya que esta localidad mantiene una de las poblaciones más grandes en Lima. Tomamos medidas corporales y datos reproductivos e hicimos un total de 1924 capturas y recapturas. La baja capturabilidad resultó en la subestimación de la población los meses más fríos, con fluctuaciones entre 69 y 313 en adultos y entre 88 y 351 en juveniles, a lo largo del año, para el total de 6.07 ha del sitio de estudio. La capturabilidad incrementó los meses más cálidos donde la población adulta estimada alcanzó su máximo entre diciembre y enero, mientras que los juveniles mostraron un pico en diciembre y otro en abril. Se observó dimorfismo sexual, siendo las hembras 8% más grandes que los machos. El ciclo reproductivo es similar al que presentan otras especies en zonas templadas donde las hembras tienen huevos oviductales en primavera, y la aparición de individuos juveniles ocurre de mediados a finales del verano cuando la comida es abundante. Se recomienda realizar una evaluación anual en Huaca Pucllana y en otras localidades de ocurrencia de estos geckos durante el verano. Además, recomendamos llevar a cabo un programa de manejo que incluya la translocación de individuos entre Huaca Pucllana y las cuatro localidades más cercanas.

The Lima Leaf-Toed Gecko (*Phyllodactylus sentosus*) is a nocturnal lizard endemic to Peru, considered as critically endangered by the International Union for Conservation of Nature and Natural Resources. They are known only in 10 sites located in Lima City and one apparently isolated population located 318 km (straight line) to the south-southeast from the southernmost record in the Ica region (Venegas et al., 2017). The sites are isolated from each other and characterized by a dry environment where the vegetation is scarce or absent (Cossios and Icochea, 2006; Pérez et al., 2013; Olivera et al., 2016; Venegas et al., 2017). The small area that this species occupies and the small number of localities, with other records of its presence, are the main reasons to consider these geckos among the species most threatened with extinction (Pérez and Balta, 2016).

The low number of localities in which a species exists implies a greater probability of extinction because of the possibility that when the environment changes in one site, a high percentage of the species' habitat disappears (Terborgh, 1974). However, other factors need to be taken into account to have a clear picture of the conservation status of a species (Foley, 1994). Population size is one of the most important factors, as it is related to the vulnerability of a population to natural disasters and stochastic changes of genetic, demographic, or environmental nature (Shaffer, 1981; Frankham, 1996), and consequently, it is considered the most determining factor for the risk of extinction of a species (Reed et al., 2003).

In this paper, we present the results of population size and population dynamics assessments we conducted between May 2011 and April 2012 at Huaca Pucllana, which has one of the healthiest populations of the Lima Leaf-Toed Geckos (Cossios and Icochea, 2006). Our general hypothesis was that environmental factors influence the size and population dynamics of the Lima Leaf-Toed Geckos. We examined the monthly variation of the population size and the influence of temperature and humidity on catchability, as well as reproductive patterns throughout a year of study. The purpose of these evaluations was to produce useful information for decision-making purposes regarding the management and conservation of this endangered species.

Materials and Methods

Study Site.—We carried out the study at Huaca Pucllana (Fig. 1), a pre-Columbian archaeological site built with mud bricks in an arid area located in the district of Miraflores in Lima City, the capital of Peru. This site, of approximately 6.07 ha, is surrounded by streets, houses, and gardens, which are inappropriate habitats

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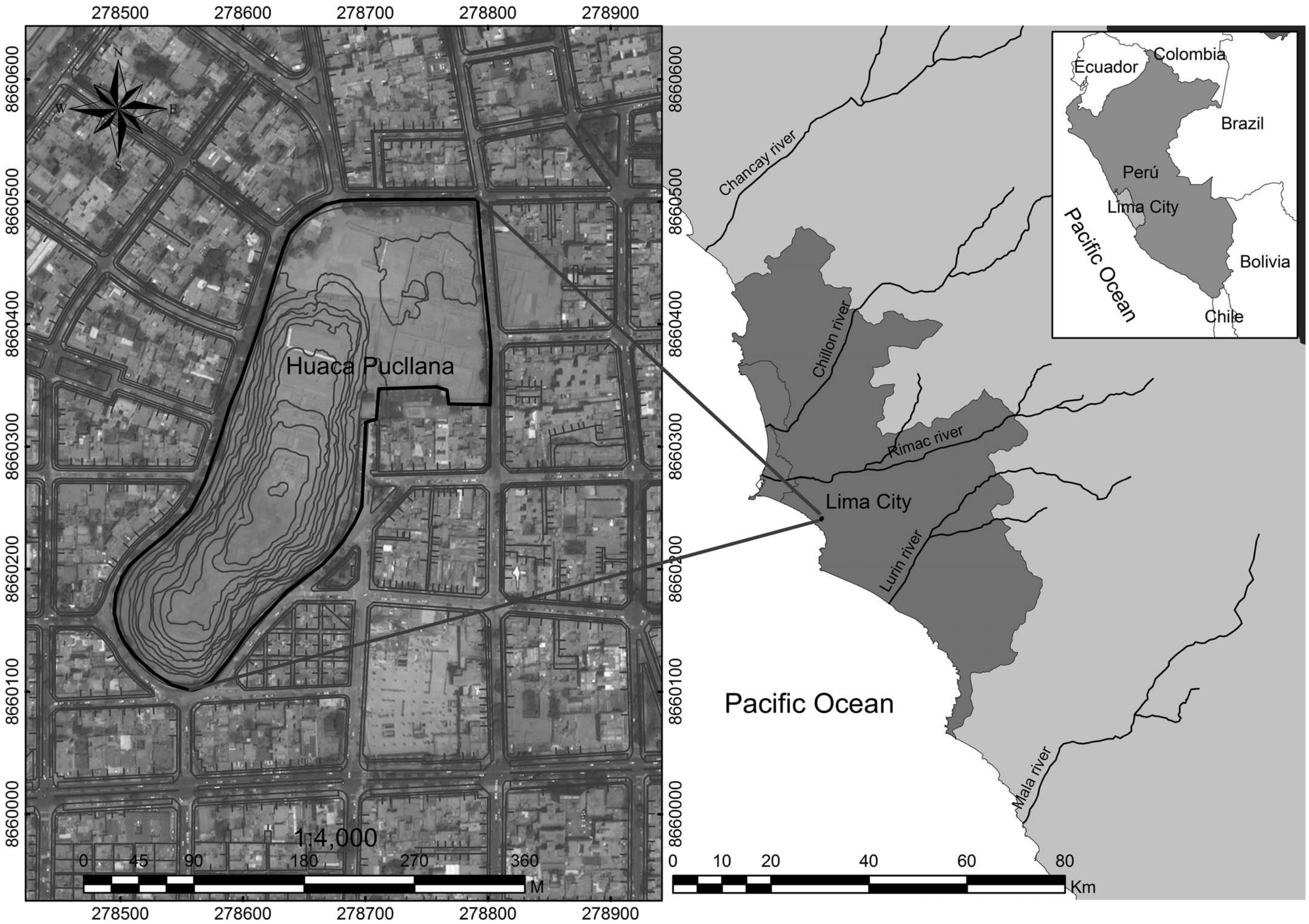

FIG. 1. Map of the study site of the Lima Leaf-Toed Gecko (*Phyllodactylus sentosus*) population in Lima, Peru.

for the geckos (Fig. 2) and keep them as an isolated population. During the population assessments, we covered 77% of the total area, equivalent to 4.67 ha. We did not evaluate the remaining 23% (1.4 ha), as it was not accessible.

Population Size.—We conducted 12 capture and recapture campaigns between May 2011 and April 2012 (Table 1). Each campaign consisted of four evaluation nights. Because of the isolated location of the site and the short duration of the campaigns, we considered the geckos' population as closed, which means without significant emigration, immigration, death, or birth events during each campaign. We performed the work between 1900 and 2300 h, as the Lima gecko is a nocturnal species. Each night, a team of three people captured geckos with their hands, covering the whole study area. We photographed each gecko on graph paper, marked them on one leg with a red nail polish dot, and released them. Using lanterns, gravid females were identified by the visible eggs in the abdomen through the backlight effect. In the first month, we made two marks on each gecko to verify whether the marks faded in a period of 5 d (Seber and Felton, 1981).

Each night, we marked a different leg, so we could know on which night each gecko was captured or recaptured. We identified the sex of adult individuals by the presence or absence of a protuberance of the skin, which evidences the existence of a hemipenis, and analyzed the proportion between adult males and females using a chi-square test. We differentiated adults and juveniles because of the shorter size and

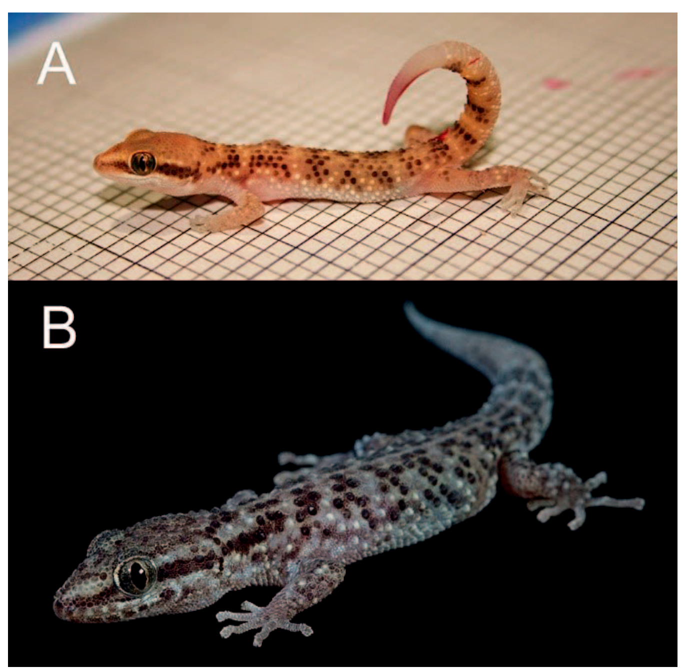

FIG. 2. Lima Leaf-Toed Geckos (*Phyllodactylus sentosus*) captured over the course of the study in Huaca Pucllana. (A) Juvenile. (B) Adult.

Table 1. Captures and recaptures of Lima Leaf-Toed Geckos (*Phyllodactylus sentosus*) per month, population density, and estimated abundance for the sampled and the total study areas in Huaca Pucllana. (n.a. = estimation not available).

			Population size (SE) 4.67 ha		Density (individuals/ha)		Total population 6.07 ha		
Month, Year	Captures	Recaptures	Adults	Juveniles	Adults	Juveniles	Adults	Juveniles	Total
May 2011	141	20	130 (14)	176 (15.7)	29	38	169	229	398
Jun 2011	75	12	93 (11.7)	100 (12)	20	21	121	130	251
Jul 2011	53	12	53 (8.8)	71 (9.9)	11	15	69	92	161
Aug 2011	45	2	n.a.	68 (10)	n.a.	14	n.a.	88	n.a.
Sep 2011	58	13	89 (11.4)	73 (10.1)	19	16	116	95	210
Oct 2011	82	17	123 (13.5)	82 (10.45)	26	17	160	106	266
Nov 2011	110	28	143 (14.4)	150 (14.5)	31	32	186	195	381
Dec 2011	172	41	224 (17.7)	200 (16.8)	48	43	291	260	551
Jan 2012	133	40	241 (18.5)	100 (11.3)	52	21	313	130	443
Feb 2012	115	36	163 (15.1)	142 (13.9)	35	30	212	184	396
Mar 2012	127	34	175 (16)	158 (14.6)	37	34	227	205	433
Apr 2012	153	45	130 (13.7)	270 (19.2)	28	58	169	351	520

orange color of the latter. We did not identify the sex of juveniles because of the difficulty of observing their hemipenis. Although some adults may have similar characteristics to the ones described herein for juveniles, the lack of permits to euthanize individuals of this species, considered critically endangered, made dissection for confirmation impossible. Conspicuous juvenile coloration is not very common (Cott, 1940), but is present in some species and may indicate age (Kemp, 2006; Hawkins et al., 2012), as in the case of Lima Leaf-Toed Geckos.

We analyzed the capture–recapture data using the CAPTURE software (Otis et al., 1978; White et al., 1982; Rexstad and Burnham, 1992) developed for closed-population models. This software uses a discriminant analysis function in its model selection procedure to determine which best suits the available data and additionally includes a closure population test. CAPTURE allows the investigator to choose the best-fitting model of seven, considering the following sources of variation: individual heterogeneity (model M_h), behavioral response to the capture (model M_b), time (model M_t), and a mixed source of variation (models M_{bh}, M_{th}, and M_{tb}). The seventh model, M_o, assumes no variation in capture probability associated with individuals or occasions. We estimated capture probability, abundance, and estimated standard error of abundance (SE) using CAPTURE. We multiplied the population density, expressed as the number of individuals/ha, by the 6.07 ha of Huaca Pucllana to obtain an estimate of the total population.

Humidity and Temperature Influence.—We took temperature and relative humidity values using a thermohygrometer (REED Instruments, model LM-81HT) between 2000 and 2100 h of every working day. We carried out a Pearson correlation test with these data to verify whether these environmental factors influenced the ease in capturing geckos.

Body Length.—We used the photographs taken on graph paper to measure the snout–vent length (SVL). We ordered the SVL data in class intervals following the Sturges rule (Sturges, 1926). For the male, female, and juvenile groups, we developed body length distribution curves for each month and for the whole data. Finally, we evaluated whether there were differences in size between males and females using a *t*-test and the formula used by Fitch (1981) with other gecko species of the Phyllodactylidae family:

$$\mathrm{FMR}=\left(\frac{\mathrm{MeanF}}{\mathrm{MeanM}}\right)\times 100$$

FMR = Female-to-male ratio.

Results

Population Size.—We made a total of 1,924 captures and recaptures over the course of this work. The number of individuals captured by month fluctuated between 45 and 172 ($\bar{x} = 105.3$, standard deviation [SD] = 19.09), whereas the number of recaptures varied between 2 and 45 ($\bar{x} = 25$, SD = 14.11; Table 1). No loss of marks was noted in the first month, which showed that enamel marking is a suitable method for a period of 5 d.

For all cases, closure test results indicated that there was no violation of the closed population assumption. To choose the model for estimating the population of adults and juveniles we assessed the results on a monthly basis, as suggested by CAPTURE's algorithm (software). We estimated population sizes on 24 occasions. We selected the best-fit model for our data showing the lowest SE. Throughout this procedure, we chose the M_h (model incorporating individual heterogeneity) as the best fit (rated near 1), which makes use of the jackknife estimator to calculate the adult population ($\bar{x} = 0.6$, SE = 14) and the young population ($\bar{x} = 0.7$, SE = 13) on a monthly basis.

The population size estimates based on analysis using CAPTURE varied from 53 to 241 ($\bar{x} = 142.18$, SD = 56.42) adult individuals and from 68 to 270 ($\bar{x} = 132.5$, SD = 62.19) juveniles per month (Table 1). The adult population in August was the only case where it was not possible to estimate population size because of the low number of captures and recaptures. The highest number of adult individuals was captured and recaptured in December and January; during these months the estimated population peaked, whereas juveniles showed peaks in December and April (Fig. 3). According to the population size estimates for the 4.67 ha evaluated, density varied from 11 to 52 ($\bar{x} = 30.54$, SD = 12.17) adults and from 14 to 58 ($\bar{x} = 28.25$, SD = 13.51) juveniles per hectare, and we estimated the total population to vary between 69 and 313 ($\bar{x} = 184.81$, SD = 73.18) adults and between 88 and 351 ($\bar{x} = 172.08$, SD = 80.94) juveniles for the whole 6.07 ha of the site (Table 1). There was a strong positive correlation between the catchability and temperature ($r = 0.72$, df = 46, $P < 0.005$) and a moderate negative correlation between catchability and humidity ($r = -0.42$, df = 46, $P < 0.005$).

The number of adult males and females captured per month varied from 4 to 58 ($\bar{x} = 26.5$, SD = 15.91) and from 10 to 54 ($\bar{x} = 31$, SD = 13.19), respectively, and the sexual proportion was between 0.2 : 1 and 1 : 1 (Table 2). The proportion in the captures remained stable during almost the entire study; July was the only month in which the sex ratio of the captured individuals

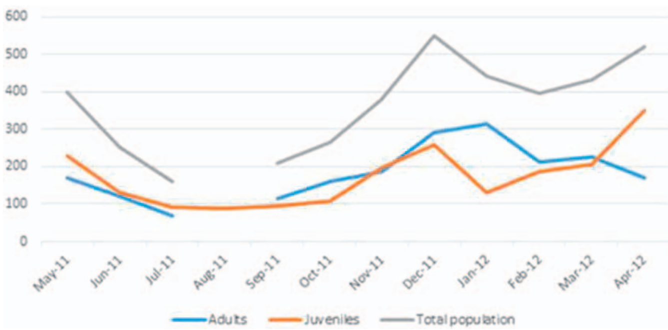

FIG. 3. Monthly population estimates of the adults, juveniles, and total Lima Leaf-Toed Geckos (*Phyllodactylus sentosus*) in Huaca Pucllana using the CAPTURE software and the M_h model between May 2011 and April 2012. The population estimate in August is missing because of small sample size.

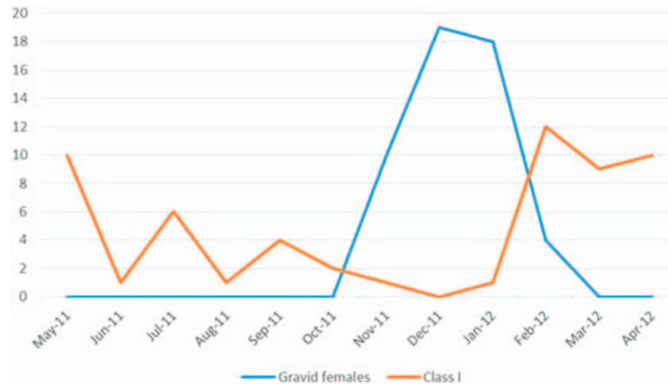

FIG. 4. Number of gravid female and juvenile Lima Leaf-Toed Geckos (*Phyllodactylus sentosus*) belonging to the smallest size category, captured by month between May 2011 and April 2012 in Huaca Pucllana.

was significantly different ($\chi^2 = 5.47$, $n = 23$, $P = 0.01$), with a value of 0.2 : 1. We captured gravid females only between November 2011 and February 2012 (Table 2). Fifty-one gravid females were captured, 47 of them having one oviductal egg and 4 of them having two.

Body Length.—Following the Sturges rule (Sturges, 1926), we organized the SVL data in XII class intervals, named here from I to XII.

The adult-male SVL data varied from 32.7 to 66.4 mm ($\bar{x} = 49.9$, $n = 318$) and concentrated in the class intervals VI and VII, which contained 13.9 and 13.0% of the individuals respectively. The adult-female SVL data varied from 29.1 to 74.7 mm ($\bar{x} = 53.4$, $n = 372$) and were more common in the class intervals VII (12.7%) and IX (8.5%). Finally, the juvenile SVL data varied from 23.1 to 49.8 mm ($\bar{x} = 33.4$, $n = 790$), mainly occupying the class intervals II and III (Fig. 5). The Fitch formula gave a result of 108% ($n = 620$), indicating that females were 8% longer than males, and the t-test was significant ($t = 7.811$, df $= 577.78$, $P < 0.005$), showing sexual dimorphism. The number of juveniles belonging to the smallest size category (class I) varied from 0 to 12/mo, being more abundant in February (Fig. 4).

DISCUSSION

Population Size.—The Lima Leaf-Toed Gecko population in Huaca Pucllana is small, with fewer than 70 adult individuals captured in the coldest months of the year and about 300 in the warmest months. Several authors have estimated the minimum size of a population to maintain a tolerable level of inbreeding (e.g. Shaffer, 1981; Frankham, 1995). Although the belief that a minimum viable population can be calculated for individual species has been largely discredited in conservation biology, the fact that small populations are more affected by demographic stochasticity and genetic drift is fully accepted (Lande, 1988; Kohn et al., 2006). The observed variation of the total number of adults during the study is likely because of a behavioral response (Huey and Pianka, 1977; Huey, 1982; Stevenson, 1985; Losos, 1987). Time constraints of daily or seasonal activity during winter resulted in the population underestimation because of the low catchability during that period. The Lima Leaf-Toed Gecko showed sensitivity toward the temperature, confirming our hypothesis statement. Moreover, the continuous presence of juveniles of sizes belonging to the first category of development throughout the year demonstrates a slow growth rate, a trait that implies longevity as reported in geckos of temperate regions (Greer, 1989; Webb et al., 2008), rejecting the idea of seasonal variations of the population size.

Body Length.—The only measures of Lima Leaf-Toed Geckos published previously correspond to three males (mean SVL = 50.9) and three females (mean SVL = 47.3) (Dixon and Huey, 1970; Venegas et al., 2017). Our results, on the basis of the measurement of 286 males and 334 females, improve the knowledge about the size of this species. In addition, our results

TABLE 2. Number of Lima Leaf-Toed Gecko (*Phyllodactylus sentosus*) adult males, adult females, juveniles, gravid females, and juveniles belonging to the smallest size category (class I) captured per month over the course of the study in Huaca Pucllana. The probability of recapture of males, females, and juveniles for each month is shown in parentheses.

Month, Year	Males	Females	Juveniles	Sex ratio (M : F)	Gravid females	Class I (23–27.5 mm)
May 2011	27 (0)	27 (3.7)	87 (21.6)	1 : 1	0	10
Jun 2011	15 (11.8)	23 (4)	48 (15.8)	0.7 : 1	0	1
Jul 2011	4 (20)	19 (5.3)	40 (21.6)	0.2 : 1*	0	6
Aug 2011	8 (0)	10 (0)	31 (0)	0.8 : 1	0	1
Sep 2011	19 (13.6)	20 (0)	32 (25.6)	1 : 1	0	4
Oct 2011	22 (8.3)	29 (0)	47 (26.6)	0.8 : 1	0	2
Nov 2011	30 (16.7)	26 (6.5)	74 (23.7)	1 : 0.9	10	1
Dec 2011	49 (25.4)	50 (12.9)	92 (20)	1 : 1	19	0
Jan 2012	58 (12.1)	54 (16.2)	53 (28.4)	1 : 0.9	18	1
Feb 2012	34 (20)	43 (16.7)	74 (22.9)	0.8 : 1	4	12
Mar 2012	35 (15)	39 (2.4)	85 (28.6)	0.9 : 1	0	9
Apr 2012	17 (13.6)	32 (5)	141 (26.2)	0.5 : 1	0	10

* Significantly different with a chi-square test.

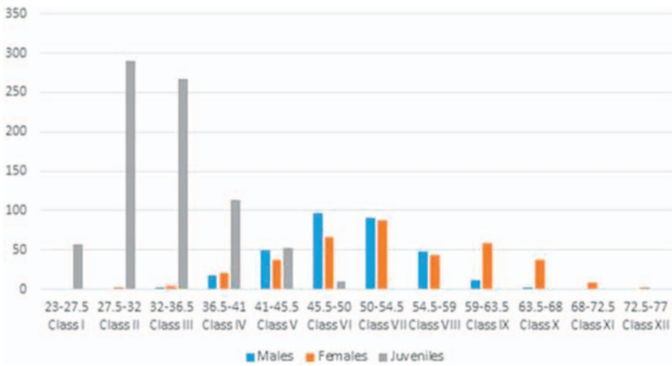

FIG. 5. Size structure for the snout–vent length of the Lima Leaf-Toed Gecko (*Phyllodactylus sentosus*) population in Huaca Pucllana. Bars show the number of males, females, and juveniles captured over the course of 1 yr for each size class. Size intervals are expressed in millimeters.

show, unlike the average results obtained by Dixon and Huey and Venegas et al., that females of this species are, on average, significantly larger than males. This sexual dimorphism with larger females is not common in the genus *Phyllodactylus*. In the study of 10 South American species of this genus, this type of dimorphism was only found for *Phyllodactylus lepidopygus* (Fitch, 1981).

Reproductive Cycle.—Most species of the genus *Phyllodactylus* show extended periods of reproduction, producing multiple clutches, and the females contain mature eggs in most seasons of the year (Goldberg, 2007), a typical pattern in reptiles of tropical areas. In contrast to this, *P. sentosus* showed a reproductive cycle more similar to the species that inhabit temperate zones, where females have oviductal eggs in spring and summer, and the hatchlings appear in the late summer and autumn when food is abundant (Goldberg, 2007). This reproductive pattern is present in lizards from temperate areas, such as *Phyllodactylus xanti* from California (Goldberg, 1997) and in other reptiles from the Northern (Fitch, 1970; Duvall et al., 1982; Licht, 1984; Goldberg, 2007) and Southern hemispheres (Aun and Martori, 1994; Cruz, 1994; Ibargüengoytía and Casalinas, 2007). Such a strategy results in growth of juveniles and the accumulation of fat, thus allowing entry to the winter period with sufficient reserves (Duvall et al., 1982; Goldberg, 2007). This reproductive pattern would correspond to species adapted to the weather of Lima City, which presents a marked difference in temperature and humidity between summer and winter.

Conservation Implications.—To monitor the population at Huaca Pucllana, we recommend conducting population estimates once a year: between December and February, as this is the period when catchability was the highest and researchers can make estimations with the lowest standard error to verify the interyearly population fluctuation. Similar evaluations in the other localities where the species also occurs are recommended, to have a better understanding about the conservation status of the species.

Before the modern urban development of the city of Lima took place, much of the area now occupied by the city had a dry environment similar to that of Huaca Pucllana so that the population of Lima geckos likely had a much larger distribution, perhaps uninterrupted between most of its currently known localities. In such a scenario, the inbreeding and probability of loss of genetic variability would have been much lower than at present. To reverse this situation, we propose carrying out a management program that includes the translocation of individuals between Huaca Pucllana and the four closest localities (Mateo Salado, Huallamarca, Parque de las Leyendas, and San Marcos) which, together with Huaca Pucllana, occupy the northwest of the city (Cossios and Icochea, 2006) and very likely constituted a single population in the past. The translocation of reptiles is a usual practice in conservation and to mitigate conflicts between humans and wildlife (Germano and Bishop, 2009). There are studies of successful translocation cases of geckos and other squamates (Burton and Rivera-Milán, 2014; Knox and Monks, 2014; McCoy et al., 2014).

When translocating this species, the main goal should be to maintain a flux of spawning individuals (adult males and females) necessary to reverse the effects of endogamy and the loss of genetic variability as a result of genetic drift (Simberloff, 1988). A variety of factors needs to be taken into account, such as the availability of food and other resources in the receiving site (Armstrong et al., 2002), the presence of predators and competitors (Bramley and Veltman, 1998), and the season (Eastridge and Clark, 2001), prioritizing dates near the reproduction season, when the individuals are most active.

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