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Dissertação de Mestrado:

Abundance of Amazona vinacea at Western Santa Catarina, Brazil

Mestranda: Viviane Zulian Orientador: Gonçalo Ferraz

Coorientadora: Eliara Solange Müller

Universidade Federal do Rio Grande do Sul – Instituto de Biociências – Programa de Pós-Graduação em Ecologia Av. Bento Gonçalves, 9500 – Setor 4 – Caixa Postal 15007 91501-970 – PORTO ALEGRE – RS Fone (51) 3308 7623 Fax (51) 3308 7626 Home: www.ecologia.ufrgs.br E-mail – ppgecol@ufrgs.br

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Abstract

Amazona vinacea is an endangered species, with an apparent dependence of *A*. *angustifolia*, using the seeds of this species as food resource and local to roost. *A. vinacea*, as most of Psittacidae species, congregates in collective roosts during the non-reproductive period. This behavior facilitates counts of the population for abundance estimates. Our work was focused to produce an *A. vinacea*'s abundance estimate at western Santa Catarina, Brazil based on roost counts. Our methodology was developed to considering the principals sources of uncertainty; the presence of roost, the movements of individuals between monitored roosts, imperfect detection during the counts and the possibility of double counts. We used Binomial N-Mixture Models with non-independent detection to analyze the data in a Bayesian framework. We did 103 roosts counts in six roost areas that are outside the IUCN extant distribution area of *A. vinacea*. We estimated a population of 941 \pm 50 individuals (maximum count 696).

Considering the confidence intervals of the abundance estimated (860 – 1047 individuals), the density of *A. vinacea* in WSC is between 0.025 and 0.031 individuals/km². Using the same density for the entire IUCN extant distribution for the species, we estimated a global abundance of 4,128 individuals (c.i. between 3,686 and 4,570). There was no obvious synchrony in the temporal variation of the number of individuals on different roosts. It is important to concentrate more efforts on mapping the distribution and monitoring the species' abundance integrating different types of data.

Keywords: Psittacidae, imperfect detection, Vinaceous Parrot, endangered species.

Introduction

Trees of the Araucaria genus originated before the breakup of Gondwana, more than 170 million years ago (Escapa & Catalano, 2015), and are among the oldest plant living fossils. These Gymnosperms where ubiquitous in both hemispheres during the Jurassic and gradually gave way to Angiosperm dominance, being restricted nowadays to Melanesia, Australia, New Zealand, and South America (Kershaw & Wagstaff, 2003). The extant Araucaria species with the largest geographic range, Araucaria angustifolia, survived dramatic climate change over hundreds of millions of years (Behling 1998), and now occurs prominently in the Araucaria sub-region of the Atlantic forest of Southern Brazil, Northern Argentina and Eastern Paraguay (Veblen et al. 2005). Adult individuals of A. angustifolia emerge above the canopy of angiosperm trees and produce large amounts of highly nutritive seeds at a time of the year when other resources are scarce (Mantovani, Morellato, and Reis 2004). The species thus provides safety and food for a large number of animals, and is likely a vital resource for a handful of vertebrate species (Vieira and Iob 2009). Among the birds, three species stand out for their association with A. angustifolia (Anjos 2009): one passerine, the Araucaria Tit- spinetail (Leptasthenura setaria); and two parrots, the Red-spectacled Amazon (Amazona pretrei) and the Vinaceous-breasted Amazon (Amazona vinacea).

As the heavily logged Araucaria forests of the Mata Atlantica lose ground to industrial agriculture and tree farming (Ribeiro et al. 2009; Fearnside 2001; Baptista and Rudel 2006), the survival of the associated fauna is at risk. Knowledge of the natural history and population dynamics of the threatened species becomes a key tool for their conservation. Of the three species of birds mentioned in the previous paragraph, *L. setaria* is clearly restricted to *A. angustifolia* forests (Remsen 2017). *A. pretrei* feeds on a variety of resources other than *A. angustifolia* seeds (Prestes, Martinez, and Peres 2008), but during winter the whole population congregates near an area of high

Araucaria density where they eat mostly Araucaria seeds (Martinez and Prestes 2008). The least known and most endangered of the three bird species is *A. vinacea* (BirdLife International 2016). With a range that overlaps with, but goes beyond the range of *A. angustifolia* (Carrara et al. 2008; Cockle et al. 2007), the Vinaceous-breasted Parrot is remarkably unpredictable in its spatial distribution. The species' movements appear to cover such long distances that they might well be dependent on *A. angustifolia* seeds at some time of the year throughout their range, but we don't know enough about the distribution and abundance of the species to understand the extent of its dependence on Araucaria, and hence, it's most basic habitat needs. Much of the future conservation of *A. vinacea*, as with any other species, depends on obtaining sufficient of its distribution and abundance as they vary through time and space (Norris 2004).

The IUCN range of *A. vinacea* covers an area of 117,500 square kilometers, from Paraguay, in the East, to southern Espírito Santo state, in the west (BirdLife International 2016). This map consists of five large patches with tens of thousands of square kilometers each, and eleven small patches that have up to a few hundred square kilometers. Such heterogeneous distribution reflects not only the species' true range, but also the scarcity of information about the movements of *A. vinacea* individuals. The large patches correspond to extensive areas of suitable habitat within which the species has been reliably found; the small patches are locations of roosts or breeding sites where the species has been detected though not as reliably as in the larger areas. The annual life cycle of *A. vinacea* is part of the challenge in understanding its range. Breeding *A. vinacea* individuals disperse in pairs throughout the range between July and December. Towards the end of the breeding season, from December to January, they start congregating every evening in roosts that they may or may not use throughout the entire non-breeding period (Zulian 2014). The number of roosting individuals can vary over three orders of magnitude both between roosts and between different times on the same roost during the January-June non-breeding

season. When August begins, there are virtually no parrots left on the roosts and the population is once again dispersed across hundreds of nesting sites whose location is better known to nest poachers than to ornithologists. Despite the difficulty in counting parrots at a roost and the unpredictability of movements during the non-breeding season, roost counts are at present the most effective way of assessing the population size and delimiting the distribution range of the species.

Roost counts can be obtained in many different ways but they always involve locating roosts, choosing the appropriate time for counting, and actually counting a number that is as close as possible to the real number of animals present in the area. In order to improve knowledge of the distribution and abundance of A. vinacea from roost counts, one should approach these three tasks of locating, timing and counting roosts in a way that minimizes five key sources of uncertainty about the end result. The first and second sources have to do with locating roosts. First, there is uncertainty about the extent of A. vinacea's distribution. When does an isolated patch in the range map represent an isolated population vs. an isolated observation of individuals that use a wide unmapped area? The second source is uncertainty about density of roosts at the local to regional scale. At what point should one stop spending resources on finding more roosts, versus dedicating time to studying the known roosts in detail? The third source of uncertainty pertains to the movement of individuals between roosts and conditions the timing of counts: if roosts or counting sites correspond to isolated local populations, different roosts could be counted at any time throughout a non-breeding season. If, on the contrary, individuals move between roosts, then such movements have to be accounted for, or counts have to be simultaneous. The fourth and fifth sources of uncertainty relate to the counting technique by itself and address, respectively, false negative and false positive observations of A. vinacea individuals. A false negative, or detection failure, happens when a parrot that is present at a site is not counted because it was not seen. A false positive happens when a parrot is counted twice by mistake.

This paper first estimates the abundance of *A. vinacea* for Western Santa Catarina (WSC), one focal part of the species' range that happens to be outside the IUCN map, and subsequently extrapolates that number to obtain an estimate of the global number of *A. vinacea* individuals in 2016. Our study is entirely based on roost counts and it seeks to address all five sources of uncertainty listed in the previous paragraph. The problem of false absences will be formally accounted for in the statistical modeling of our data, and the remaining four sources of uncertainty will reflect on sampling design decisions and on the assumptions of the extrapolation from the WSC to the global estimate. Because there is an ongoing debate about the possibility of down-listing *A. vinacea* from Endangered to Vulnerable status in the IUCN Red List of Threatened Species, we discuss our results in the light of other population size numbers and offer a contribution to the debate which quantifies uncertainty about the estimated population size.

Methods

Study area: We sampled in the western part of the Brazilian state of Santa Catarina (WSC; Fig. 1), a rectangle-shaped area of 34,000 km² (IBGE 2015) extending West-



Fig. 1. Extant geographic range of Amazona vinacea according to the IUCN Red List of Threatened Species (dark gray), and our study area of Western Santa Catarina (light gray) (BirdLife International, and Handbook of the Birds of the World, 2016).

East between the Uruguay River (to the South) and the ridgeline that separates the Uruguay and Iguaçú watersheds (to the North). On its West and East ends, the area confines with two relevant patches of *A. vinacea* habitat, respectively, the Atlantic Forest of the Argentinian Province of Misiones, and the Araucaria forests of Eastern Santa Catarina (Fig. 2). Besides the strategic location, WSC is unique for having a surprisingly high frequency of *A. vinacea* sightings (WikiAves 2008) in an area that is almost entirely (88%) outside the IUCN extant range of the species (Fig. 1). WSC falls within the Araucaria forest and the Interior forest biogeographic sub-regions of the Mata



Fig. 2. Study area of Western Santa Catarina (light gray) and regional forest cover (dark gray). The figure represents every patch of forest (excluding tree farms) with more than five square kilometers, according to the Brazilian Ministry of the Environment's Mapa de Cobertura Vegetal dos Biomas Brasileiros. White circles show the location of all presently known WSC roosts with their name abbreviations: PS (Palma Sola), CE (Campo Erê), GT (Guatambú), SD (São Domingos), AL (Abelardo Luz), and AG (Água Doce).

Atlantica, which have lost, respectively, 87 and 93% of their forest cover since the onset of European colonization (Ribeiro et al. 2009). Nowadays, the remaining forest patches in WSC (Fig. 2) are surrounded by agro-industrial development, consisting mostly of soybean, eucalyptus, and pine tree plantations (Fearnside 2001; Baptista and Rudel 2006). All of the six known *A. vinacea* roosts in WSC coincide with tall (>10m) Araucaria forest patches, and all but two (Palma Sola, and São Domingos) have very open to non-existent understory vegetation under the Araucaria canopy (Fig. 2).

Data collection: Fieldwork took place from December 2015 to July 2016, during the *A*. *vinacea* non-breeding season, and consisted of monthly visits to all known roosts of the species in WSC. Visits lasted from four to six days, during which we counted the number of individuals present at each roost between one and four times. Counts started at dawn (30 minutes before sunrise) or dusk (90 minutes before sunset) and lasted until we could not detect parrot movement into or out of the roost for 20 minutes – which always happened within two hours of the beginning of the count. We visited every roost before the first count to establish three observation lookouts per roost, in strategic locations for observing the arrival and departure of parrots. Each count was performed by a team of

three observers (one at each lookout) equipped with a roost area map, a compass, an audio recorder, and a radio to communicate with other observers about parrots going their way. Every time an observer saw one or more A. vinacea individuals, he recorded the number of individuals, the time, and the direction of flight, as well as any other comments that could help understand the movement of the birds. At the end of each count, the team of three observers met to compare their notes and agree on one 'most reasonable' (MR) and one 'highly conservative' (HC) count result. The difference between MR and HC results lies on how observers treat the possibility of double counting. Suppose, for example, that an observer sees five parrots arriving at a roost and a few minutes later sees another arrival of three individuals. Based on this information, the MR count result is of eight individuals. Suppose further, however, that one of the observers in the trio heard calls of unseen moving parrots during the time that separates the two observations above. In this case, the team might judge that there was some, however small, possibility that the second group of three was a subset of the first group of five who had left undetected and returned within sight. If that were the case, the HC count result should be five and not eight, because five is the absolute minimum number of birds that the team is sure to have seen arriving at the roost.

The consideration of MR and HC count results addresses one source of uncertainty about *A. vinacea* abundance estimates: the possibility that some animals may be counted more than once. There is, however, a second source of uncertainty that deserves attention, which is the possibility of detection failure, i.e. that some animals are not counted even though they are present at the roost. To address detection failure, we replicated our counts by working simultaneously with two teams of three observers, at the same roost and time. We placed two observers (one from each team of three) at each of the lookout points, keeping sufficient distance between observers to preclude overhearing radio communications. Furthermore, we ensured that observers from different teams did not exchange any information about their observations until the end of the meeting where each team

separately agreed on its count results. We thus treat every team-specific count of a given roost and month, whether at dawn or dusk, as an independent sample of that roost for that month.

Data analysis: We analyzed MR and HC counts as separate data sets, each summarized by a data array C with dimensions S by K by T, where S = 6, the number of roosts, K = 4, the maximum number of counts per roost in any given month, and T = 8, the number of sampling months. Elements C_{iik} of this three-dimensional array give the number of parrots counted at the j^{th} count of the i^{th} roost in the k^{th} month, with i = 1, ..., S, j =1, ..., K, and k = 1, ..., T. In order to estimate the number of parrots per roost per month, we model the data for each month separately, using an N-mixture model (Royle 2004), which represents the number N_{ik} of individuals in roost *i* and month *k* as a Poisson distribution with parameter λ_k . For simplicity, we drop the subscript k from the notation below, but do keep in mind that we model each month separately and therefore have monthly estimates of the Poisson parameter and of the number of parrots on each roost. The most straightforward implementation of Royle's (2004) model accounts for imperfect detection by modeling the counts C_{ij} as the result of a binomial sample with N_i independent trials and probability of success ρ (which also takes a different value every month). The Binomial distribution, however, implies that the probability ρ of detecting one individual parrot is independent of the other parrots; this would be reasonable if parrots moved about independently of each other but they don't, they form groups of variable sizes where large, more noisy groups are easier to detect than small groups. To address this problem, we followed Martin et al. (2011)'s approach of modeling detection as a Beta-binomial distribution, with parameters N_i , ρ and ρ , where ρ is a correlation parameter that accounts for heterogeneity in detection probability. In practice, this solution amounts to using a Binomial distribution with a random ρ , which

comes from a Beta distribution. In short, our model combines the biological variation of abundance among roosts with the sampling process of parrot detection:

$N_i \sim \text{Poisson}(\lambda)$ $C_{ij} \sim \text{Binomial}(N_i, \rho \rho).$

We fit this model to each month's and to each type of count result (MR or HC) in a Bayesian framework, using non-informative priors. The model implementation used the BUGS language (Lunn et al. 2000) running on JAGS (Plummer 2003), using code adapted from Kéry and Royle (2015, chap. 6). To draw from the posterior probability distribution of the parameters, we used an MCMC algorithm with three chains, 25,000 iterations and a burn-in of 5,000 implemented in the software JAGS. All chains converged to R-hat < 1.1.

Results

Month		N	p
December	(MR)	286±8 (265)	0.87±0.03
	(HC)	275±11 (244)	0.79±0.03
January	(MR)	439±28 (335)	0.68±0.04
	(HC)	386±28 (297)	0.67 ± 0.05
February	(MR)	941±50 (696)	0.67 ± 0.03
	(HC)	953±57 (670)	0.62 ± 0.04
March	(MR)	678±9 (639)	0.88±0.01
	(HC)	612±7 (588)	0.92±0.01
April	(MR)	729±29 (562)	0.64±0.02
	(HC)	750±34 (538)	0.57 ± 0.02
May	(MR)	565±28 (446)	0.72±0.03
	(HC)	612±42 (414)	0.59±0.04
June	(MR)	840±13 (761)	0.81 ± 0.01
	(HC)	798±13 (724)	0.80±0.01
July	(MR)	395±21 (321)	0.74±0.04
	(HC)	353±4 (286)	0.75±0.04

Table 1. Estimated number of individuals (N) and detection probability (p), by month, for the aggregate of all roosts sampled in this study. The numbers in parentheses show aggregate count, based on the sum of the highest count of each roost for the corresponding month. The two rows per month separate estimates based on the 'most reasonable' (MR) and the 'highly conservative' (HC) count results.

We completed eight field trips to the study area, sampling every known roost on every trip, monthly, from December 2015 to July 2016. Since one of the roosts was found in

February (*Abelardo Luz*) and another in May (*Campo Erê*), we started out by sampling four roosts in December, increased to five in February, and finally to six in May. In total, we completed 103 roost counts, with an average of 2.5 counts per roost per trip (minimum of 1 and maximum of 4). Comparison of the MR and HC results from each count reveals that while MR values were always higher, as expected, they were also less variable (Table 1). Accordingly, when fitting models to MR and HC results separately, estimates of detection probability (p) and the precision of abundance estimates (N) were generally higher for the MR than for the HC results. We will, for this reason, focus on the MR results in the remainder of the paper. We will refer to MR counts simply as 'counts', and specify 'HC counts' when we refer to the highly conservative results.



Fig. 3. Monthly counts and estimates of the number of Amazona vinacea individuals in WSC according to the 'most reasonable' (MR) count results. Gray lines show 95% credibility intervals around the estimated number of individuals.

Looking at the aggregate of all roosts, we found the lowest number of individuals in the two extremes of the non-reproductive period (Table 1; Fig. 3): in December, with a maximum count of 265 and *N* of 286 ± 8, and in July with a maximum count of 321 and *N* of 395 ± 21 individuals. The highest *N* was estimated in February, at 941 ± 50 individuals (maximum count 696), while the highest count was obtained in June, with 761 individuals across all roosts. Only three roosts – *Abelardo Luz, Água Doce*, and *Guatambú* – reached *N* estimates in excess of 200 (Table 2). All roosts showed substantial variation in *N*

between months but there was no obvious synchrony in the temporal variation of the number of individuals on different roosts. While *Abelardo Luz* had the highest *N* in June, *Água Doce* peaked in March, and *Guatambú* did so in April.

Likewise, the minimum values of N were obtained in December, January, March, and June, depending on the roost. Looking at the spatial distribution of roosts in Figure 2, and the distribution of N values in Table 2, it becomes apparent that the northeast of the study area (Abelardo Luz and Água Doce) concentrated between 56 and 90% of the population during the last three months of the sampling period.

Month \ Ro	oost	Palma Sola	Campo Erê	Guatambú	São Domingos	Abelardo Luz	Água Doce
December	(MR)	12±2 (10)	-	165±4 (155)	83±3 (75)	-	26±1 (25)
	(HC)	12 2 (0)		157.5 (142)	00.4(71)		25.2 (22)
		12±2 (8)		15/±5 (143)	80±4 (71)		25±2 (22)
January	(MR)	86±7 (65)		221±11 (175)	27±6 (10)		104±7 (85)
	(HC)		-			-	
		73±7 (53)		193±10 (158)	25±6 (10)		95±7 (76)
February	(MR)	132±9 (101)		193±11 (141)	103±8 (77)	139±13 (77)	373±16 (300)
	(HC)		-				
		131±10 (94)		195±13 (137)	107±9 (75)	149±14 (77)	371±17 (287)
March	(MR)	74±3 (68)		60±3 (51)	31±2 (25)	19±2 (14)	494±5 (481)
	(HC)		_				
		66±2 (63)		50±2 (47)	27±2 (24)	16±1 (14)	453±4 (440)
April	(MR)	28±6 (5)		244±9 (197)	58±4 (39)	77±6 (48)	321±10 (273)
	(HC)		_				
	. ,	36±7 (5)		252±10 (191)	64±5 (35)	78±8 (42)	321±11 (265)
May	(MR)	40±5 (25)	40±5 (25)	60±5 (40)	75±5 (58)	137±6 (114)	211±8 (184)
	(HC)						
	. ,	50±7 (21)	52±7 (24)	69±8 (36)	73±8 (45)	151±9 (110)	218±11 (178)
June	(MR)	5±2 (0)	5±2 (0)	41±3 (29)	33±3 (24)	450±5 (433)	307±5 (275)
	(HC)			38±3 (26)	31±3 (22)	429±5 (409)	290±5 (267)
		5±2 (0)	5±2 (0)	. ,	. /	. /	. ,
July	(MR)	37±3 (31)	57±4 (46)	20±3 (12)	57±4 (45)	168±7 (143)	57±4 (44)
-	(HC)						
	. /	34±3 (30)	46±4 (37)	14±3 (8)	53±4 (42)	157±7 (131)	48±4 (38)

Table 2. Monthly counts and estimates of the number of individuals in each roost throughout the study period based on the 'highly conservative' (HC) and the 'most reasonable' (MR) count results. The numbers in parentheses correspond to the highest count for the corresponding roost and month. Roost order corresponds to longitudinal position, with Palma Sola, the easternmost roost, appearing in column 1. The Abelardo Luz and Campo Erê roosts have fewer months of data because they were discovered after the beginning of the sampling period.

Considering the area of WSC and the 95% credibility interval for the February

(maximum) aggregate estimate of abundance ($N = 941 \pm 50$; c.i. = [860, 1047]), we

estimate the density of A. vinacea in WSC to be between 0.025 and 0.031 individuals per

square kilometer. Extrapolating this density to the entire area of the IUCN extant

geographic range (~145,700 km²), we obtain an estimated global population size of 4,128

individuals, with a 95% credibility interval between 3,686 and 4,570 individuals.

Discussion

Our estimate of $941 \pm 50 A$. *vinacea* individuals for WSC, extrapolated to the entire IUCN extant range of the species, provides a global population estimate of 4,128 individuals in 2016. This extrapolation, obtained under the assumption of homogenous population density, can be compared with the most recent 'World Count' of *A. vinacea* roosts, a sum of non-replicated, direct counts of the number of individuals seen at roosts across the range of the species, including the roosts from our study (Martinez and Prestes 2016, pers. comm.). Our extrapolated global estimate exceeds the 2016 World Count of 3,920 by 208 individuals, yet its 95% credibility interval of 3,686 to 4,570 includes the Count by a wide margin. The similarity between the direct count and the extrapolated value is no proof that the density is homogenous, but it is remarkable that the similarity holds under such simplifying assumption, given the differences in space, time, observation technique, and analysis that lie behind the results. Further consideration of these two results should help inform decisions about *A. vinacea*'s threat category in the IUCN Red List of Threatened Species.

IUCN's criterion C for the classification of species in the 'Endangered' threat category states that a species should be considered endangered if its population is 'estimated to number fewer than 2,500 mature individuals' *and* it fulfills either of two conditions about inferred population trend (BirdLife International 2001). Given the short temporal scope of our study, we will not examine the trend conditions, but we can ask whether the 2016 population is below the threshold of 2,500 mature individuals. To do this, we must specify what proportion of the estimated population consists of mature individuals. From the IUCN's range of 'precautionary' numbers for total and mature population size, we derive a range of proportions of mature individuals from 0.60 to 0.68. If, taking the midpoint of that range, one considers a proportion of 0.64 and multiplies that proportion by the 2016 World Count result, the 2016 estimate of the number of mature

individuals becomes 2,509, just above the IUCN threshold. Applying the same reasoning to the extrapolated results, the global number of mature individuals becomes 2,642 with a 95% credibility interval from 2,359 to 2.929. In the latter case, we cannot exclude the possibility that the number of mature individuals is below the IUCN threshold. Our analysis of *A. vinacea* abundance provides no basis for a category change; we suggest that the species should remain in the 'Endangered' IUCN threat category, until there is more evidence to suggest the contrary. Incidentally, our results also illustrate how a model-based estimate that accounts for uncertainty in the observation process – the extrapolated number with its credibility interval – can be more conservative than a deterministic result, based on direct counts of the minimum number of individuals believed to be present at each roost – the World Count. The apparent contradiction in this finding underscores the importance of considering uncertainty in the assessment of species extinction risk (Mace et al., 2008; Regan et al., 2005; Wilson, Kendall, & Possingham, 2011).

Clearly, the assessment of extinction risk will be as good as the underlying estimates of population size. Our estimate for WSC and its extrapolation are far from perfect, but they address a variety of sources of uncertainty that ought to be accounted for as formally as possible in future monitoring efforts. At the broadest level, there is uncertainty about the range of the species, both within and beyond WSC. We tried to reduce this uncertainty within WSC by dedicating one day of every field trip to searching for new roosts. The effort returned a 50% increase in the number of sampling sites over the duration of the study, but we covered the northern half of the region in more detail than we covered the southern half, which has only one known roost (Guatambú; Fig. 2). One should expect more roosts in the north, because it has more Araucaria forest and a higher density of large ($\geq 5 \text{ km}^2$) forest patches; yet, judging from the distribution of sightings in WikiAves (Wikiaves 2008) and verbal reports from the area, we believe there are more regular roosting sites to be found in the southern part of WSC. Considering that all the Vinaceous Parrots detected in this study were observed outside the IUCN range, uncertainty about as the sume to the sume results.

range extends well beyond the limits of WSC. The small dots suggestive of isolated populations in the IUCN range map may be a useful starting point for improving knowledge about the species distribution. Most of these dots are likely part of larger areas of continuous use by *A. vinacea* individuals.

A second source of uncertainty is the possible variation in density (individuals per unit area) across the species' range. This is particularly relevant to our extrapolated global estimate, as the validity of the extrapolation relies on the assumption of homogenous density. There are two good reasons to question this assumption. The first is that densities tend to be low at the edge of distribution ranges (Brown, Stevens, & Kaufman, 2003; Gaston, 2009). Such pattern is supported by the relatively lower counts found in Argentina and Paraguay (Cockle et al. 2007; Segovia and Cockle 2012) when compared with those of eastern Santa Catarina (Nêmora Pauletti Prestes et al. 2014). A second reason is the substantial difference in number of known roosts per unit area (roost density) between WSC and the IUCN range. Roost density may give a biased impression of individual density because the number of individuals per roost varies over three orders of magnitude; nonetheless, roost density numbers weigh against the homogeneity assumption because there are, on average, many more roosts per unit area in the IUCN range than in WSC. Dividing the 60 World Count sites outside WSC (most of which are roosts) by the IUCN area, one obtains an average of 1, 9×10^3 km² per site in the IUCN range; in WSC, the corresponding number is 5, 7×10^3 km². In light of this information, if the number of individuals per roost is sufficiently stable across the range, our extrapolation should be an underestimate of the true global population. This is plausible, despite the similarity between the extrapolated estimate and the deterministic count discussed above. Since the deterministic counts do not correct for imperfect detection and estimates of detection probability range from 0.59 to 0.92 (Table 1), the sum of counts is likely to be an underestimate as well. Lacking more robust information about population density outside

WSC, we find it reasonable to draw a conservative, first estimate of global population size based on the assumption of homogenous density. It is important, however, that this first estimate is taken as what it is—a rough approximation. Replication of counts within short periods over a larger part of the species range will certainly help account for geographic changes in density and improve knowledge of global population size.

Homogenous or non-homogenous, the distribution of A. vinacea individuals throughout the species' range is certainly dynamic. Such dynamism is unequivocally supported by the disappearance of individuals from roosts during the breeding season and by the variation in WSC roost estimates throughout the study (Table 2). This brings up a third source of uncertainty, about movement of individuals between roosts, which we tried to address in this work. We estimated the lowest numbers of individuals on all WSC roosts in December and July (Table 1), the first and last months of the sampling period, but the variation of abundance through time (Table 2) was far from synchronous across roosts. Indeed, the roosts at São Domingos and Abelardo Luz had their lowest estimates in January and March, respectively-not at the extremes of the sampling period. If there were a gradual accumulation and subsequent loss of individuals from all roosts with a peak somewhere in the middle of the non-breeding period, we would be inclined to believe that each roost aggregates individuals that breed in the surrounding area. The irregularity of temporal variation in roost size, however, suggests that A. vinacea individuals probably move well beyond the immediate surroundings of one roost as they track resources during the non-breeding season (see also (Forshaw 2010; Nêmora Pauletti Prestes et al. 2014). As a result, individuals counted at one roost in a given month, may very well be present at a different roost in another month. This is why we based our WSC estimate on the month with the highest estimate (February) and not on a sum of each roost's highest monthly estimate. Uncertainty about movement is also the reason behind concentrating counts in as short a period as possible, both in our monthly WSC counts and in the World Count.

So far, we discussed three sources of uncertainty that are mostly biological in nature – uncertainty about range limits, about spatial distribution of abundance, and about movements between roosts. Another two sources of uncertainty – double counting and detection failure – are more methodological in nature, but they also guided relevant decisions of our study design and data analysis. In the context of this study, double counting happens when observers overestimate the number of parrots in a flock and when parrots move out of sight and are mistakenly counted as different individuals when they reappear. Our consideration of MR and HC counts was an attempt to evaluate the consequences of being less or more conservative about the possibility of double counting. The consequences were negligible: the 95% credibility intervals of the MR and HC-based estimates for WSC overlapped in all but two months. In those two months (June and July), the difference between point estimates was of 42 individuals.

The tendency for higher precision in MR than HC estimates stems from a greater agreement among MR, than among HC counts of the same roost and month. This is no proof that MR counts are indeed closer to the true value, but it does strengthen our reliance on the MR estimates.

The second methodological source of uncertainty is the inevitable failure to detect some of the parrots that are present at a site. Despite all our efforts to surround the roosts, work with three-observer teams, and connect members of each team by radio, the counts taken by different teams at the same place and time still differed. We conclude that this is not a problem to be eradicated – as it cannot possibly be – but to be accounted for. It is reassuring to see that detection probability (*p*) was estimated to be always greater than 0.5, but its variation through time makes it clear that detection failure can't be measured once and used to correct all the counts from then on. Under our modeling approach, the fact of p < 1 should be addressed by replicating counts and estimating *p* during every time period for which we want to estimate *N*. It should be noted that *p* did not go up monotonically from the beginning to the end of the sampling period, as part of the field team got more $\frac{17}{17}$

experienced with the species, the sites, and the logistics. On the contrary, p varied from month to month without any apparent trend, reaching its maximum in March and its minimum in April (Table 2). This suggests that detection failure is not so much a matter of observer experience, as a matter of atmospheric conditions, observer luck, and unpredictable parrot movements.

Of the three bird species that are tightly associated with A. angustifolia forests, A. vinacea, is the one in most urgent need of study. The very real pressures of habitat loss (Ribeiro et al. 2009) and nest poaching (Wright et al., 2001) caused an obvious but poorly documented population decline. Any efforts to protect the species will benefit from improved knowledge of population size and structure. We hope that our approach to estimating population size in WSC will motivate others to obtain replicated counts of roosts elsewhere in the species range. In an attempt to coordinate observers and gather count information, we set up an online count-reporting tool where users can access existing data and contribute their own. The current version is available in Portuguese at: http://vivianezulian.azurewebsites.net/. The uncertainty surrounding local and global population estimates, however, is still high enough to justify monitoring the species with a wide variety of observation techniques. On one front, citizen science networks such as WikiAves, Xeno-Canto, and eBird can offer valuable information for mapping the species range and reproductive areas. On the other, molecular analysis of parrots across the range can help understand seasonal movements and the spatial structure of the population. Progress in both fronts will require formal integration of different types of data into one statistical model of the species distribution and abundance. Any progress in the molecular front will require development of effective and safe techniques for obtaining A. vinacea DNA without endangering the sampled individuals.

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