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Satellite imagery reveals new critical habitat for Endangered bird species in the high Andes of Peru

Phred M. Benham[1], Elizabeth J. Beckman[1], Shane G. DuBay[1], L. Mónica Flores[2], Andrew B. Johnson[1], Michael J. Lelevier[1], C. Jonathan Schmitt[1], Natalie A. Wright[1], Christopher C. Witt[1,*]

[1]Museum of Southwestern Biology and Department of Biology, University of New Mexico, Albuquerque, New Mexico 87110, USA

[2]Centro de Ornitologia y Biodiversidad (CORBIDI), Urb. Huertos de San Antonio, Surco, Lima, Peru

ABSTRACT: High-resolution satellite imagery that is freely available on Google Earth provides a powerful tool for quantifying habitats that are small in extent and difficult to detect by medium-resolution Landsat imagery. Relictual *Polylepis* forests of the high Andes are of critical importance to several globally threatened bird species, but, despite growing international attention to *Polylepis* conservation, many gaps remain in our knowledge of its distribution. We examined high-resolution satellite imagery in Google Earth to search for new areas of *Polylepis* in south-central Peru that potentially support *Polylepis*-specialist bird species. In central Apurímac an extensive region of high-resolution satellite imagery contained 127 *Polylepis* fragments, totaling 683.15 ha of forest ranging from 4000 to 4750 m a.s.l. Subsequent fieldwork confirmed the presence of mature *Polylepis* forest and all 6 *Polylepis*-specialist bird species, 5 of which are considered globally threatened. Our findings (1) demonstrate the utility of Google Earth for applied conservation and (2) suggest improved prospects for the persistence of the *Polylepis*-associated avifauna.

KEY WORDS: Satellite imagery · Google Earth · High Andes · *Polylepis* forest · Habitat conservation · *Cinclodes aricomae* · *Leptasthenura xenothorax* · *Anairetes alpinus*

INTRODUCTION

A key first step in conservation is to assess the quantity and quality of existing habitat. Satellite imagery has been widely recognized as a powerful tool for the quantification of habitats (Skole & Tucker 1993, Butler 2006, Asner et al. 2009) provided that it is combined with on-ground assessment of habitat condition and population status for species of concern (Mawdsley 2008, Cook et al. 2010). Although medium-resolution satellite imagery has previously been used to track change over time in habitat extent or quality (e.g. Houghton et al. 1991, Echeverria et al. 2006, Asner et al. 2009), it is inadequate to detect habitats that are difficult to identify, small in extent, or patchily distributed (Matos et al. 1992). Images taken over the last decade by DigitalGlobe's Quickbird satellite at ~2.5 m resolution are becoming freely available in Google Earth and have been implemented for >20% of the Earth's landmass (Potere 2008). Where they exist, these images now provide an unparalleled resource for conservation, allowing cost-free quantification and georeferencing of threatened habitats.

Polylepis forests of the high Andes are considered one of the most threatened forest ecosystems in the world (Renison et al. 2005), due to the persistent threats of forest burning as a means of increasing pasture area (Renison et al. 2006), livestock grazing preventing regrowth (Teich et al. 2005), and direct cutting of *Polylepis* trees for firewood (Lloyd & Marsden 2008). Despite the critical state of these forests, conservationists still lack basic distributional knowledge of these

*Corresponding author. Email: cwitt@unm.edu

forests due to the extreme topography, harsh climate, and a limited existing road network, all of which hamper exploration in the high Andes. Further, *Polylepis* forests were already severely reduced in extent before the digital age (Fjeldsa 2002b), and what remains is often too small to be reliably detected using medium-resolution Landsat imagery (Matos et al. 1992, Aucca & Ramsay 2005).

Six bird species are considered to be strict *Polylepis* specialists (Fjeldsa & Kessler 1996, Stotz et al. 1996), and their persistence is tightly linked to the fate of *Polylepis* forests. Due to the ongoing destruction of *Polylepis* forests, 5 of these species are now considered globally threatened (BirdLife International 2010), making the preservation of *Polylepis* forests a top priority for South American bird conservation (Fjeldsa 1993, 2002a,b, Lloyd & Marsden 2008). In order to best preserve the biodiversity associated with *Polylepis* forests, Fjeldsa (2002a) recommended that conservation efforts focus on centers of endemism, which are regions characterized by aggregations of range-restricted species. Three key centers of endemism exist in Peru and Bolivia and together contain about half of the globally threatened bird species in the Central Andes. One of these target areas, centered in the Cusco-Apurímac region of south-central Peru, harbors populations of the 5 globally threatened *Polylepis* specialists: white-browed tit-spinetail *Leptasthenura xenothorax*, tawny tit-spinetail *Leptasthenura yanacensis*, royal cinclodes *Cinclodes aricomae*, ash-breasted tit-tyrant *Anairetes alpinus*, and giant conebill *Oreomanes fraseri.* Currently, these species are only known in the Cusco-Apurímac region from a handful of sites in the Cordillera Vilcanota, Cordillera Vilcabamba, and Cerro Runtacocha highlands (Fjeldsa & Krabbe 1990, Engblom et al. 2002, Lloyd 2009a).

Polylepis forests and associated specialist bird species in the department of Cusco have been the subjects of several ecological studies and ongoing conservation efforts (Parker & O'Neill 1980, Engblom et al. 2002, Lloyd 2008a,b,c, Lloyd & Marsden 2011). *Polylepis*-specialist bird species have received less attention in Apurímac, where they are only known from the Cerro Runtacocha highlands in the northern part of the department. The full extent of *Polylepis* forests in high-altitude areas of Apurímac has never been assessed in detail, and the potential for new populations of *Polylepis*-specialist bird species seems high, given the geographical proximity to the Runtacocha highlands and extensive land area above 4000 m elevation. In Apurímac, high-resolution satellite imagery can potentially facilitate accurate estimation of *Polylepis* cover, identification of new patches, and on-ground assessment of their characteristics and fauna. In the present study, we examined high-resolution satellite images to identify and quantify new patches of *Polylepis* forest that might contain *Polylepis*-specialist species in Apurímac. We then visited these newly identified forest patches to determine patch quality and population status of globally threatened *Polylepis*-specialist bird species in the area.

MATERIALS AND METHODS

Satellite imagery. We used Google Earth to search for *Polylepis* habitat in the Apurímac region, focusing on 1 contiguous area of high-resolution imagery that contained potential *Polylepis* habitat outside the known range of *Polylepis* forests in Apurímac. Google Earth reprojects satellite images using the WGS-84 datum with excellent horizontal positional accuracy (average error is ~40 m), although the methods employed for spectral transformation or spatial interpolations of satellite imagery have never been made public (Potere 2008). Most of the Earth's land area is covered by medium-resolution Landsat imagery in Google Earth; however, an ever-growing patchwork of high-resolution (~2.5 m resolution) imagery from DigitalGlobe's Quickbird satellite is also available.

The size of the high-resolution area that we studied in Apurímac was ~1054 km^2, extending from 13° 47′ to 14° 20′ S and 73° 07′ to 72° 57′ W (Fig. 1). Imagery dates of 16 May 2006 and 17 June 2007 were provided by Google Earth and presumably correspond to the dates on which the Quickbird satellite captured the images. Hereafter, we will refer to this region as the high-resolution satellite image around Anchicha (HRSIA). The area of apparent *Polylepis* forest was centered ~50 km SSW of the city of Abancay in the Chacoche district, province of Abancay, department of Apurímac (Fig. 1).

To guide our examination of the HRSIA, we used known *Polylepis* forest patches of the Cordillera Vilcanota, Cusco, as a search image for new patches in Apurímac. *Polylepis* patches in the Cordillera Vilcanota that we had personally visited were easily visible in 2.5 m resolution images. We searched for individual tree crowns that appeared as puffy green objects with distinct shadows, and contiguous patches of trees that looked darker, rougher in texture, and greener than the background color of surrounding non-*Polylepis* habitat (Fig. 2). We also assumed that any patch of forest detected on satellite images above 4000 m represented *Polylepis* forest. We systematically searched the HRSIA for *Polylepis* patches and used the polygon tool in Google Earth Pro to quantify the area of polygons drawn by eye around the perimeter of each *Polylepis* patch. This method produces conservative patch size estimates because it uses horizontal positional coordinates to calculate area without accounting for eleva-

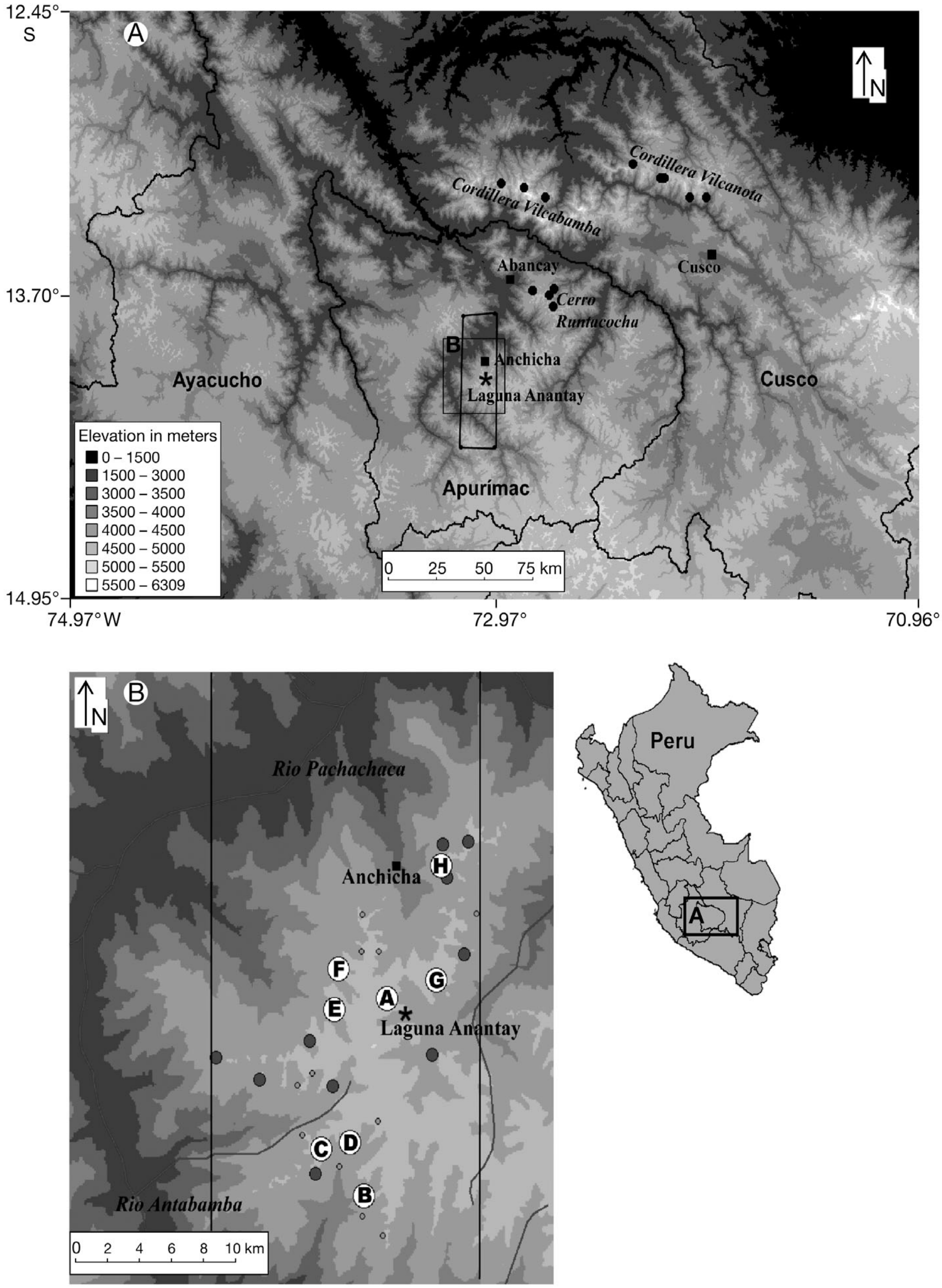

Fig. 1. (A) Map of the Apurímac-Cusco region in southeast Peru. Locations of previously known *Polylepis* sites (●) and human population centers (■) are indicated relative to our camp at Laguna Anantay (⋆). Black boxes show the extent of the high-resolution satellite image around Anchicha (HRSIA) and the area enlarged in Panel B. (B) Map of the HRSIA. Eastern and western boundaries of the HRSIA are denoted by vertical lines. The northern and southern extents of the HRSIA did not contain *Polylepis* forest and are excluded from the image. A to H indicate valleys containing at least 1 large patch of *Polylepis* forest (see Table 1). Additional medium (4 to 12 ha) and small (<4 ha) forest patches that occur distant from large patches are marked as large dark gray and small light gray circles, respectively. A map of Peru showing the study area is provided for orientation

tion. A patch was considered to comprise any contiguous area of forest separated from other fragments by 30 m or more. Patches were categorized following Lloyd (2008a), with modifications to accommodate a continuous range of patch sizes, as either small (<4 ha), medium (4 to 12 ha), or large (>12 ha).

On-ground assessment. We selected 1 out of the 9 aggregations of *Polylepis* forest within the HRSIA for detailed on-ground assessment of the habitat and bird community. This site, the Laguna Anantay Valley, was a west–east draining glacial valley, bisected by a rushing stream, the flow of which was obstructed by a moraine to form a 12 ha lake (14° 03′ 40″ S; 73° 00′ 05″ W; 4360 m elevation). This valley was best suited for our fieldwork because it contained ~15% of the visible *Polylepis* forest on the HRSIA and it was accessible within a short hike from a rough, but drivable track that ascended from the small town of Anchicha to access a small gold mine. We visited the area on 6 December 2009 and between 6 and 15 January 2010. The study area consisted of 285 ha, encompassed the full extent of the *Polylepis* forest surrounding Laguna Anantay, and extended to the road on the eastern side of the valley. We visually confirmed that the forest was comprised of *Polylepis* on the basis of the trees' characteristic shaggy, reddish bark and compound, serrate leaves. The geographical extent of the forest patches was confirmed using a handheld, altimeter-assisted GPS unit (Garmin 76CSX). Elevations determined from the digital elevation model implemented in Google Earth were confirmed using the GPS unit to within 30 m. We characterized typical forest structure in 2 plots of 10 m radius that were selected using random compass bearings and distances from a central point within the largest forest patch. In each plot we measured stem diameter at breast height for all woody plants over 2 m in height, stem density for woody plants over 2 m in height, stem density for woody plants under 2 m in height, average canopy height, and percent canopy cover.

We estimated the relative abundance of bird species by 2 separate methods: (1) capture rates from mist-nets and (2) daily censuses. These 2 complementary methods were used because each is associated with distinct detection biases (Remsen & Good 1996). The mist-netting effort was comprised of 36 nets and 1015 net-

Fig. 2. Satellite image of Laguna Anantay Valley. (A) Main camp. (B) Largest patch of *Polylepis* (71.39 ha) extending along the entire north slope of the valley. (C,D) Two 10 ha patches in the southwestern part of the valley. White outlined Xs represent vegetation data points; white rectangles represent localities of the thirty-six 12 m mist-nets. Multiple nets that were placed end-to-end are represented by only a single white rectangle. Nets are illustrated at 4 times their actual size

hours divided among *Polylepis* forest interior (13 nets, 363 net-hours), *Polylepis* forest edge (16 nets, 477 net-hours), and grassy habitats in the inter-patch matrix (7 nets, 175 net-hours; Fig. 2). Mist-nets were 12 × 2 m, and mesh size varied from 32 to 36 mm. Nets were checked every 20 min and closed during periods of precipitation. Every capture was recorded, and identification was confirmed by at least 2 experienced observers. Birds were marked before release by making a small clip on the vane of 1 rectrix to avoid counting any individual more than once. Capture rates for each species were calculated as the ratio of total number of individuals caught to total mist-net hours. Only the first capture for each individual was included in the calculation of capture rate. As many species as possible were documented by photograph, voice recording, or, for non-threatened species, voucher specimens. Media files, specimens, and specimen data were deposited at Centro de Ornitología y Biodiversidad (CORBIDI; Lima, Peru) and the Museum of Southwestern Biology (MSB; Albuquerque, New Mexico, USA). All methods were approved in advance by the University of New Mexico Institutional Animal Care and Use Committee (Protocol 08UNM033-TR-100117).

Daily censuses of the Laguna Anantay Valley were conducted from 7 to 14 January 2010 and, on the initial visit to the valley, on 6 December 2009. Daily censuses were accomplished by teams of 2 to 4 observers working together to attempt to count all of the birds present in the study area using the area search method as described by Ralph et al. (1993). Following the area search protocol, census teams of 2 to 4 observers walked a slow, 3 to 4 h loop around the valley, through all of the *Polylepis* patches, recording all individuals detected, and communicating with 2-way radios to avoid double counting of individuals. Unlike standardized transects, area search allows observers to wander within the study area to search for secretive birds, identify unfamiliar species, or make behavioral observations (Hewish & Loyn 1989, Ralph et al. 1993). We chose this method for 2 primary reasons: (1) the small, well-defined study area and simple habitat structure (65% open habitat) allow for counts that approach the true census number and (2) the short duration of our field expeditions, variable skill of our observers, and frequent inclement weather precluded application of statistically rigorous distance sampling methods such as those used by Lloyd (2008a). Due to heavy and frequent precipitation, censuses were conducted at various times of day. Following Dieni & Jones (2002), we consider our maximum daily counts to represent minimum estimates of the number of resident individuals in the study area. Total time spent conducting area searches has been found to critically affect the accuracy of counts (Slater 1994). The sum of our area search time was 110.25 observer-hours, corresponding to an average of 23.2 observer-minutes ha^{-1}.

Data from the daily censuses were used to estimate density of individuals of each *Polylepis*-specialist bird species. Density estimates were calculated by dividing the maximum single day count by the total area of *Polylepis* forest present in the study area. We extrapolated local population sizes for each *Polylepis*-specialist bird species by multiplying the density estimates from our study site by the total area of *Polylepis* within the HRSIA, under the assumption that density for each *Polylepis*-specialist species in the Laguna Anantay Valley approximates the average density among aggregations of *Polylepis* that we identified by satellite imagery but did not visit (Sites A to H in Table 1, Fig. 1B). We consider these estimates to be conservative for 3 reasons: (1) detection probability for forest species was relatively low as reflected by considerable variation in counts from one census to the next, (2) no single census could exhaustively cover the available habitat, and (3) rainy or misty conditions significantly reduced bird activity on 8 of the 9 days during which censuses were conducted. Whereas we report the total number of individuals, including juveniles that remain dependent on adults, some previous population estimates of *Polylepis*-specialist species have reported numbers of mated pairs. To help reconcile these differences, we used netting data to quantify the proportion of juveniles for each species based on plumage, gape coloration, and skull ossification.

RESULTS

Satellite imagery

Polylepis forest patches were distinctive and easy to identify in high-resolution imagery, in part because they occur at higher elevations than any other forest type. Within the entire HRSIA, we identified 127 patches of previously undocumented *Polylepis* forest, totaling 683.15 ha (Table 1) and ranging in size from 0.08 to 71.49 ha. The majority of fragments were small, but 13 large patches were found, including 3 that were >50 ha (Table 1).

Additionally, multiple clearly visible patches were found along the eastern border of the high-resolution imagery, indicating that patches of unknown extent exist within the medium-resolution imagery to the east of the HRSIA. This area of medium-resolution satellite imagery, lying between the HRSIA and the Cerro Runtacocha highlands, contains nearly continuous terrain above 4000 m and occupies an area of ~1331 km^2 (Fig. 1). If the density of *Polylepis* forest throughout the intervening region is similar to the density within

Table 1. *Polylepis* patches found within the high-resolution satellite image around Anchicha (HRSIA) on Google Earth. The top row summarizes the totals for the entire HRSIA. Sites A to H correspond to the letters in Fig. 1 and represent valleys that contain at least 1 large *Polylepis* patch. Valleys are ranked in descending order by total area of *Polylepis* occurring in the valley. Laguna Anantay was the only site that was visited during on-ground assessment

Site	Latitude (S)	Longitude (W)	Area (ha)	No. of patches by size		
				Large (>12 ha)	Medium (4–12 ha)	Small (<4 ha)
All of HRSIA			683.15	13	25	89
A	14° 02′ 32″	73° 02′ 03″	117.53	3	1	8
Laguna Anantay	14° 03′ 40″	73° 00′ 04″	101.34	1	2	6
B	14° 03′ 34″	73° 02′ 31″	75.99	2	0	2
C	14° 02′ 35″	72° 59′ 02″	73.96	2	2	11
D	13° 59′ 02″	72° 58′ 53″	31.12	1	1	1
E	14° 03′ 08″	73° 00′ 44″	29.6	1	1	1
F	14° 09′ 09″	73° 01′ 29″	16.35	1	0	3
G	14° 07′ 43″	73° 03′ 01″	14.73	1	0	1
H	14° 07′ 32″	73° 02′ 01″	13.15	1	0	0

the HRSIA (1054 km^2), then an additional 863 ha of *Polylepis* forest could potentially exist. Indeed, photos posted on Google Earth via the Panoramio application (www.panoramio.com) show dense patches of *Polylepis* forest flanking the banks of several lakes within this medium-resolution image between 4200 and 4500 m a.s.l. and located around 14° 04′ S, 72° 54′ W.

On-ground assessment

Forest patch boundaries as observed in high-resolution satellite imagery were perfectly concordant with our observations on the ground. Within the Laguna Anantay Valley there were 101.34 ha of *Polylepis* forest in 9 patches. A single large patch (71.49 ha) covering much of the north side of the valley and 2 other medium patches (ca. 10 ha) in the upper part of the valley were the largest forest fragments (Fig. 2). *Polylepis* forest at the site was largely confined to the south-facing slopes on the north side of the valley, but extended around to the south side in the upper reaches. North-facing slopes of the valley were covered mostly with *Stipu* bunch grass and rocky outcroppings. Bofedales (high-Andean bogs) bordered the main stream through the middle of the valley, with all water draining into the lake (Fig. 3A,B). *Polylepis* trees extended from 4300 to 4750 m elevation. Flanking ridges were bare rock with no permanent ice, and peaked at ~5030 m elevation on the southwestern border of the valley.

A small, subsistence community of 2 families is situated ~1.25 km E-SE of Laguna Anantay, below the extent of *Polylepis* at the site. Despite the proximity of our study site to this community, we detected little evidence of recent agricultural activity or burning at the study site. Occasionally, small numbers of livestock were seen grazing in *Stipu* bunch grass along the south side of the valley and in grassy bofedal habitat. Very little livestock manure was detected at the study site, indicating light grazing intensity (Telleria et al. 2006). In the upper portion of the valley, 2 stone corrals of unknown age were present. Signs of firewood removal were detected in only 2 spots along the edge of the largest *Polylepis* patch, and, on one occasion, we witnessed local people harvesting a small amount of *Polylepis* from a small and isolated patch adjacent to our camp.

Identification of the *Polylepis* trees to species was not possible based on photographs alone, but the dominant species present at the site is thought to pertain to an undescribed species (M. Kessler pers. comm.). Elsewhere in Apurímac *P. incana* and *P. weberbaueri* are known to occur (Fjeldsa & Kessler 1996), but their presence at Laguna Anantay remains unconfirmed. Ground cover consisted of *Stipu* bunch grass, boulder scree, or a thick layer of bark and leaf litter. Much of the boulder scree, bare ground, and tree trunks were also blanketed in moss (Fig. 3C). *Polylepis* saplings along the forest edge and openings dominated the understory. Other common plants in the forest included hanging, yellow, trumpet-shaped flowers in the genus *Salpichroa* (Solanaceae), and, along the forest edge, many ornithophilous plants, including a low-growing *Castilleja* species (Orobanchaceae) with bright red flowers. At the 2 vegetation plots within the forest (Fig. 2), average tree diameters at breast height were 57.6 cm (range: 16 to 122 cm, median: 57 cm) and 43.3 cm (range: 3.7 to 100 cm, median: 35 cm), densities of trees >2 m high were 0.232 and 0.327 trees m^{-2}, densities of woody stems <2 m high were 0.006 and 0.035 stems m^{-2}, canopy heights were 10 and 15 m, respectively; both plots were characterized by 40% foliage cover.

Birds

Fifty-two species of birds were encountered during our 9 d stay in the Laguna Anantay Valley (Table 2), including all 6 bird species considered to be *Polylepis* specialists (Table 3). The avifauna encountered at Laguna Anantay was highly similar to that of the Run-

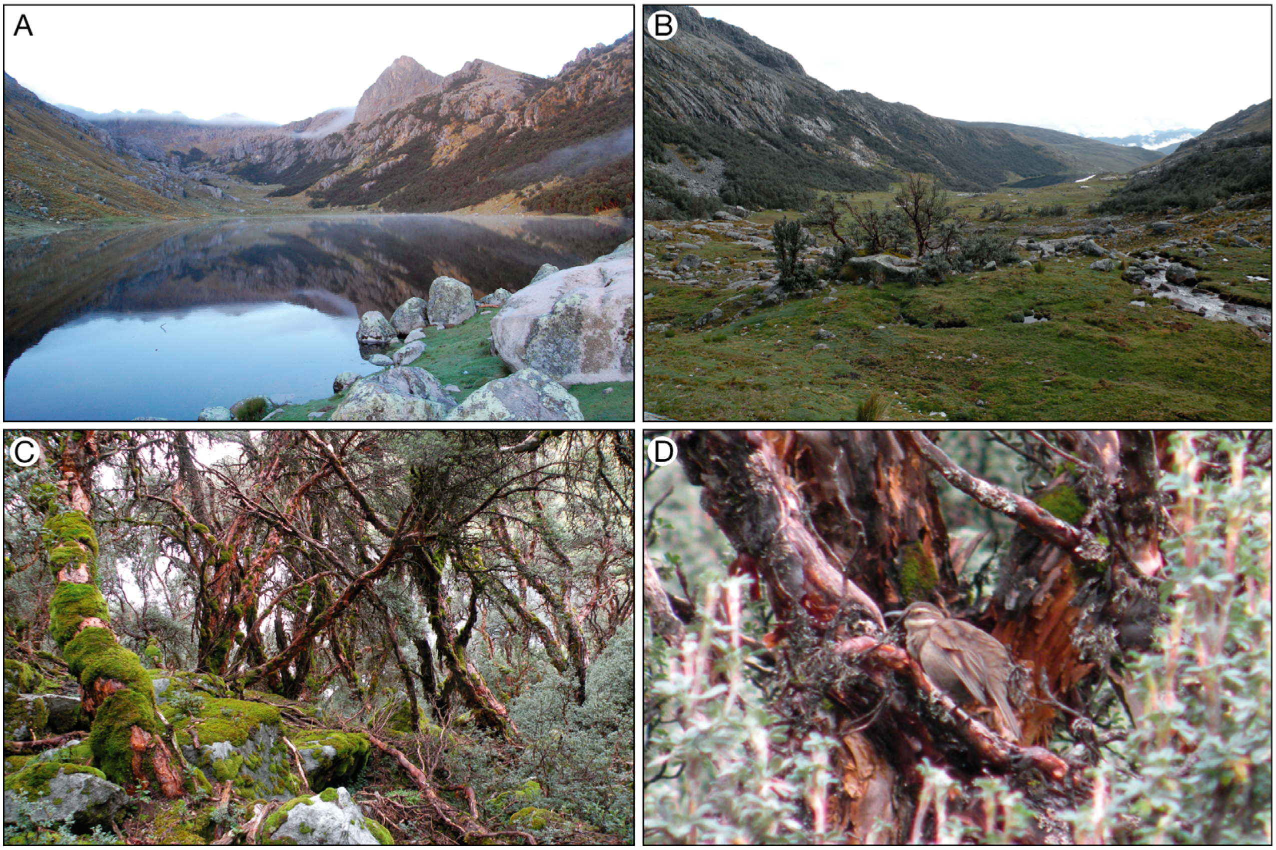

Fig. 3. (A) View westward from the main camp (ca. 4300 m a.s.l.) of the largest contiguous patch of *Polylepis* forest in the Laguna Anantay Valley, the borders of which correspond closely with the satellite image in Fig. 2. (B) View to the east from high in the Laguna Anantay Valley (ca. 4600 m a.s.l.) showing the open matrix habitat between patches also visible in Fig. 2. Even the small patch in the foreground is visible on the satellite image. (C) Interior of the largest forest patch with thick moss that is thought to be a key habitat feature for royal cinclodes *Cinclodes aricomae*. (D) Critically Endangered royal cinclodes (not captured in a mist-net) at the edge of a 10 ha patch of forest in the upper portion of the valley

tacocha highlands, 50 km to the north (Fjeldsa 1991, Fjeldsa & Kessler 1996). One exception was the absence of any *Scytalopus* species, even though a *Scytalopus* sp. nov. is known from the Runtacocha highlands and other sites in northern Apurímac. We think it is unlikely that we would have missed this species, given the extremely vocal nature of this genus at all seasons (this species was found to be vocal and abundant at a site 19 km northwest of Abancay that we also visited in January 2010). We captured 142 individuals of 25 species in mist-nets (0.140 birds h^{-1}) (Table 2) and made 1902 individual observations of 52 species during daily censuses, including all 25 species that were captured in mist-nets. Plumbeous Sierra-finch *Phrygilus unicolor* and bar-winged cinclodes *Cinclodes fuscus* were the 2 most frequently detected species at the site, both in nets and on censuses (Table 2). Both of these species were more associated with open, rocky grassland, bofedal, and forest edge habitats. Within *Polylepis* forest, house wren *Troglodytes aedon*, white-browed tit-spinetail *Leptasthenura xenothorax*, giant conebill *Oreomanes fraseri*, and ash-breasted tit-tyrant *Anairetes alpinus* were the most frequently detected species, both in nets and on censuses. All 6 *Polylepis*-specialist bird species were detected in large, medium, and small forest patches; however, our data are insufficient to examine relative abundance or density by patch size. The proportion of juvenile birds that were presumed to remain dependent on parents ranged from 22 to 29% for 4 out of the 5 species, of which we captured at least 7 individuals (*C. fuscus*, *L. xenothorax*, *T. aedon*, and *O. fraseri*). The only exception was *P. unicolor*, of which only adults were captured.

Globally threatened species

Royal cinclodes *Cinclodes aricomae*

A maximum of 12 individuals were detected within the Laguna Anantay Valley during a single daily census, and 3 were caught in mist-nets (0.003 birds h^{-1})

Table 2. Relative abundance of all 52 species detected at the study site. For each species we report the number of daily censuses (of 9 overall) during which the species was detected, the average count from daily censuses, the maximum single day count for each species, and mist-net capture rates during 1015 net hours. Documentation (Doc.) method for each species — S: specimen; P: photo; R: recording; V: visual

Species	Doc. method	No. of days detected	Daily average count	Max. single-day count	Capture rate
Nothoprocta ornata	S	1	0.11	1	0
Chloephaga melanoptera	R	9	4.00	8	0
Anas flavirostris	V	2	0.44	2	0
Lophonetta specularioides	V	1	0.33	3	0
Vultur gryphus	V	3	0.56	3	0
Phalcoboenus megalopterus	V	5	0.78	2	0
Fulica gigantea	V	9	3.00	3	0
Chroicocephalus serranus	V	2	0.22	1	0
Caprimulgus longirostris	S	2	0.33	2	0.003
Pterophanes cyanopterus	V	2	0.33	2	0
Oreotrochilus estella	S	7	3.44	8	0.005
Aglaeactis castelnaudii	S	7	1.89	6	0.006
Chalcostigma olivaceum	S	2	0.33	2	0
Chalcostigma stanleyi	V	1	0.11	1	0
Colaptes rupicola	S	8	5.00	9	0.001
Upucerthia jelskii	V	1	0.11	1	0
Cinclodes fuscus	S	9	23.78	62	0.011
Cinclodes aricomae	P	4	1.44	12	0.003
Leptasthenura xenothorax	P	9	15.56	34	0.021
Leptasthenura yanacensis	R	3	1.44	5	0
Cranioleuca albicapilla	S	5	2.56	10	0.002
Asthenes humilis	S	9	7.56	16	0.003
Asthenes virgata	S	4	1.33	8	0.002
Grallaria andicolus	S	6	4.56	13	0.002
Anairetes alpinus	P	8	10.56	21	0.007
Muscisaxicola rufivertex	S	1	0.11	1	0
Muscisaxicola griseus	S	6	4.33	15	0
Muscisaxicola juninensis	V	1	0.11	1	0
Polioxolmis rufipennis	S	9	5.67	10	0.001
Ochthoeca leucophrys	V	1	0.44	4	0
Ochthoeca oenanthoides	S	9	10.89	37	0.003
Ochthoeca rufipectoralis	S	5	1.89	7	0.006
Orochelidon murina	S	7	6.67	16	0.001
Orochelidon andecola	V	2	1.33	10	0
Anthus bogotensis	S	2	0.44	2	0
Troglodytes aedon	S	9	19.33	54	0.007
Turdus chiquanco	S	5	4.33	13	0.003
Turdus fuscater	S	1	0.22	2	0
Thraupis bonariensis	V	1	0.44	4	0
Conirostrum cinereum	V	1	0.44	4	0
Oreomanes fraseri	P,R	8	11.67	22	0.011
Diglossa brunneiventris	S	3	0.44	2	0.002
Diuca speculifera	S	8	4.55	11	0
Phrygilus plebejus	S	8	4.88	15	0.007
Phrygilus unicolor	S	9	32.11	70	0.027
Phrygilus punensis	S	4	2.11	8	0
Idiopsar brachyurus	S	2	0.56	4	0
Catamenia inornata	S	4	1.33	5	0.005
Zonotrichia capensis	S	2	0.22	1	0.002
Carduelis crassirostris	S	5	5.56	16	0.001
Carduelis atrata	S	5	1.54	6	0
Carduelis magellanica	S	1	0.33	3	0

(Table 2, Fig. 3D). We estimate that at least 81 individuals occur within the HRSIA based on a density estimate from the Laguna Anantay Valley of 0.12 birds ha^{-1}. *C. aricomae* was frequently observed in pairs, foraging on the ground within *Polylepis* forest among mossy boulders and in leaf litter, as has been described previously (Fjeldsa & Krabbe 1990, Engblom et al. 2002). Unexpectedly, pairs were witnessed twice venturing outside the edge of the forest into adjacent bofedales to feed, and were also seen making short flights across open grass and bofedal habitat between *Polylepis* patches. We also observed this species twice

Table 3. *Polylepis*-specialist bird species, as classified by Fjeldsa & Kessler (1996) and Stotz et al. (1996). Conservation status is from BirdLife International (2010). Maximum counts from daily censuses in the Laguna Anantay Valley were used to calculate the minimum density estimate for each species. Population estimates for the entire high-resolution satellite image around Anchicha (HRSIA) were calculated by multiplying each density estimate by the total area of *Polylepis* forest within the HRSIA

Species	Conservation status	Max. count	Min. density estimates (ind. ha^{-1})	Min. population size estimates in HRSIA
Cinclodes aricomae	Critically Endangered	12	0.12	81
Leptasthenura xenothorax	Endangered	34	0.34	229
Leptasthenura yanacensis	Near Threatened	5	0.05	34
Anairetes alpinus	Endangered	21	0.21	142
Oreomanes fraseri	Near Threatened	22	0.22	148
Carduelis crassirostris	Range-restricted	16	0.16	108

in crowns of *Polylepis* trees (~8 m high), calling repeatedly from a perch before descending back to the forest floor, and, on one occasion, an individual flew >100 m across open grass to an isolated grove of *Polylepis* trees. No juvenile *C. aricomae* were detected alone or traveling with adults.

White-browed tit-spinetail *Leptasthenura xenothorax*

At Laguna Anantay, this was one of the most frequently detected species, with as many as 34 individuals encountered on a single day of censuses, and 21 individuals caught in mist-nets (0.021 birds h^{-1}; 28.6% juviniles) (Table 2). From a density estimate of 0.34 individuals ha^{-1} in the Laguna Anantay Valley, we extrapolate to an estimate of 229 individuals in the entire HRSIA (Table 3). We observed *L. xenothorax* at Laguna Anantay foraging in the outer branches of *Polylepis* trees in the forest interior and at the edge, which is consistent with observations from the Cordillera Vilcanota (Lloyd 2009a), but is in contrast with those of Fjeldsa & Kessler (1996), who mention it as foraging along thick branches and the main trunk. Birds typically foraged in groups of 4 to 6 individuals, often in association with mixed species flocks that also included *Anairetes alpinus*, *Leptasthenura yanacensis*, *Oreomanes fraseri*, and occasionally *Cranioleuca albicapilla*, *Grallaria andicolus*, *Ochthoeca rufipectoralis*, *Ochthoeca oenanthoides*, *Catamenia inornata*, or *Diglossa brunneiventris.* We observed groups and individuals crossing gaps (>30 m) between *Polylepis* patches, an infrequent behavior in the Cordillera Vilcanota (Lloyd & Marsden 2011).

Tawny tit-spinetail *Leptasthenura yanacensis*

L. yanacensis was the least frequently detected of the *Polylepis*-specialist species at Laguna Anantay. Only a maximum of 5 birds were detected on censuses, and this species was never captured in mist-nets (Table 2). From a density estimate of 0.05 birds ha^{-1} in the Laguna Anantay Valley, we predict at least 34 individuals for the entire HRSIA (Table 3). *L. yanacensis* was always detected as small groups of 3 to 4 individuals traveling with mixed-species flocks (including the species listed above as foraging with *L. xenothorax*), consistent with observations in Bolivia and Peru (Herzog et al. 2002, Matthysen et al. 2008, Lloyd 2008c).

Ash-breasted tit-tyrant *Anairetes alpinus*

This was one of the most frequently encountered species, with a maximum of 21 birds detected on a single day of censuses and a total of 7 individuals netted (0.007 birds h^{-1}; 0% juveniles) (Table 2). A density of 0.21 birds ha^{-1} was estimated from census data, giving a minimum estimate of 142 individuals for the entire HRSIA (Table 3). In the Cordillera Vilcanota, Lloyd (2008b) estimated a density of 0.049 birds ha^{-1} for *A. alpinus.* Disjunct populations in the Cordillera Blanca of Ancash have been reported as rare (Collar et al. 1992), but were reported as common in the Runtacocha highlands in northern Apurímac (Fjeldsa & Krabbe 1990). We found the species foraging in pairs or flocks of up to 12 individuals, often with the same mixed-species flocks as *Leptasthenura xenothorax.* Individuals usually stayed within the forest, but were observed crossing gaps (>30 m) to forage in smaller, isolated *Polylepis* patches.

Giant conebill *Oreomanes fraseri*

This species was frequently encountered in the Laguna Anantay Valley, with a single-day maximum of 22 individuals detected on censuses, and a total of 11 individuals caught in mist-nets (0.011 birds h^{-1}; 27.3% juviniles) (Table 2). We estimate a minimum density of

0.22 birds ha^{-1} from census data, corresponding to at least 148 individuals within the entire HRSIA (Table 3). We observed *O. fraseri* in small groups of 1 to 5 birds foraging in *Polylepis* at a variety of heights and parts of the tree. *O. fraseri* was frequently seen traveling with mixed-species flocks, as has been observed throughout its range from Colombia to Argentina (Herzog et al. 2002, Matthysen et al. 2008). Although Cahill & Matthysen (2007) found birds in greatest abundance in the forest interior and areas with more mature trees, we observed *O. fraseri* foraging along forest edges and in a range of habitat types from small, scrubby patches of *Polylepis* to the dense interior of *Polylepis* forest.

Range extensions

Blue-mantled thornbill *Chalcostigma stanleyi*

Though not a strict *Polylepis* specialist, this species has a strong association with *Polylepis* and other high-elevation shrubs (Fjeldsa & Kessler 1996). *C. stanleyi* was previously known from *Polylepis* habitat in the Runtacocha highlands, 50 km to the north of Laguna Anantay (Fjeldsa 1991). One individual observed during a census on 6 December 2009 was the only detection of this species, representing a range extension of 50 km.

Great sapphirewing *Pterophanes cyanopterus*

The species was heard on 6 December, and a male and female were observed at 4650 m in a small patch of *Polylepis* forest on 13 January 2010. Both birds were observed actively chasing several other hummingbirds, including individuals of *Aglaeactis castelnaudii*. This is an exceptionally high-elevation record for this species (Schulenberg et al. 2007); however, there are previous records from *Polylepis* forest at 4500 m near Abancay (Fjeldsa & Krabbe 1990) and at 4200 m in the Cordillera Vilcanota (MSB and CORBIDI specimen data), indicating that *P. cyanopterus* does occur regularly in high-elevation *Polylepis* and probably ranges to the highest extent of the forest. Additional data are required to determine whether these observations represent opportunistic wanderings (Fjeldsa 1991) or signify that high-elevation forests comprise important habitat for this species.

White-tufted sunbeam *Aglaeactis castelnaudii*

A maximum of 6 individuals of this range-restricted, high-Andean endemic were detected on a single day of censuses in the valley, and a total of 6 individuals were netted (0.006 birds h^{-1}). Although this was one of the most abundant species in the Cordillera Vilcanota (478 birds ha^{-1}) (Lloyd 2008b), it seems to occur at low densities at our study site (0.06 birds ha^{-1}). This species ranged to the upper elevational limits of woody vegetation, at this site ~4750 m. *A. castelnaudii* was most frequently detected foraging on *Salpichroa* flowers (Solanaceae) growing on the trunks of *Polylepis* trees. In the department of Apurímac, this species has only previously been reported from the Nevado Ampay and Runtacocha highlands, ~50 km north of Laguna Anantay (Fjeldsa & Krabbe 1990, Fjeldsa 1991).

Streak-throated canastero *Asthenes humilis*

Schulenberg et al. (2007) do not show this species to occur in Apurímac, but it is known in northern Apurímac at Nevado Ampay and in the Runtacocha highlands (Fjeldsa & Krabbe 1990, Fjeldsa 1991). We found it to be common and conspicuous in open grassy habitats and on rocky outcroppings, often adjacent to the edges of *Polylepis* forest. The average number detected in daily censuses was 7.6, with a maximum count of 16. Only 3 individuals were captured in nets, but the species is difficult to capture due to its preference for open habitats.

Junin canastero *Asthenes virgata*

This species is considered range-restricted (BirdLife International 2010), with disjunct populations in the central Andes at Junin and Lima, as well as in the southern Andes in Ayacucho, Cusco, Apurímac, and Puno (Schulenberg et al. 2007). Like *Asthenes humilis*, *A. virgata* is only known in Apurímac near Abancay, 50 km to the north of Laguna Anantay (Fjeldsa & Krabbe 1990). This species was found exclusively in dense bunch grass on the valley slopes and higher ridges, in taller grass than *A. humilis.* This species was approximately half as abundant as *A. humilis* according to daily census data (Table 2), but it is more difficult to detect.

Short-tailed finch *Idiopsar brachyurus*

The presence of *I. brachyurus* at Laguna Anantay was the most surprising find of our fieldwork. This species was known previously from only 2 sites in Peru: (1) the Cordillera de Vilcanota in the department of Cusco (ca. 125 km to the northeast of Laguna Anantay) and (2) Huancasalani in the department of Puno (Fjeldsa & Krabbe 1990, Lloyd et al. 2005). Four birds seen on 6

December 2009 and a single bird collected as a voucher specimen on 14 January 2010 represent the first records of this species in Apurímac. The birds were found on grassy slopes peppered with boulders and rocky outcroppings, in close proximity to bofedal habitat and groves of *Polylepis* trees, which is generally similar to the habitat of this species described elsewhere (Lloyd 2009b).

Thick-billed siskin *Carduelis crassirostris*

This species is considered to be a range-restricted *Polylepis* specialist (BirdLife International 2010) and was previously known in the department of Apurímac only from the Cerro Runtacocha highlands, 50 km to the north of Laguna Anantay (Fjeldsa & Krabbe 1990, Fjeldsa 1991). We encountered small flocks of 3 to 15 birds during censuses around the upper edges of the valley, invariably associated with *Polylepis* forest. Only 1 bird was caught in the mist-nets. We estimate a density of 0.16 birds ha^{-1} and a corresponding population estimate of 104 individuals for the HRSIA (Table 3). Flocks consisted of males and females seen foraging on outer branches of *Polylepis* trees, probably on buds or seeds (Fjeldsa & Krabbe 1990).

DISCUSSION

Our examination of high-resolution satellite images in Apurímac revealed significant tracts of previously unrecognized high-altitude *Polylepis* forest (Fjeldsa & Kessler 1996). Subsequent on-ground exploration of the Laguna Anantay Valley confirmed the presence of dense *Polylepis* forest at the site and revealed a new stronghold for the *Polylepis* forest bird community. All 6 *Polylepis*-specialist bird species occur at the site, 5 of which are considered globally threatened (Table 3). The present study represents a range extension of at least 50 km for 11 bird species, and it adds a significant new locality for the conservation prospects of the threatened *Polylepis* ecosystem.

Previous population estimates of 50 to 250 *Cinclodes aricomae*, 500 to 1500 *Leptasthenura xenothorax*, and 250 to 999 *Anairetes alpinus* (Engblom et al. 2002, BirdLife International 2010) underscore the significance of the newly discovered populations in the HRSIA that are comprised of an estimated 81, 229, and 142 individuals, respectively. The confirmed presence of these endangered species is encouraging, but our numbers should be interpreted with caution, given the limitations of the underlying data. First, we consider our estimates of density and population size to be conservative due to the low detection probability of some species, incomplete coverage of the entire 285 ha study area during any 1 daily census, and nearly continuous inclement weather during our field study. Second, our population estimates comprise extrapolations from the Laguna Anantay Valley to all *Polylepis* patches within the HRSIA, and bird species composition may vary between patches due to differences in patch isolation, size, or quality (Lloyd 2008a). Third, 9 d of daily censuses may be too few to fully characterize the relative abundance and density of birds in the study area. Finally, the results of our daily censuses by area-search were almost certainly less precise than would be produced by standardized surveys using distance-sampling methods (Slater 1994, Dieni & Jones 2002, Lloyd 2008b).

At the time of our visit to Laguna Anantay, at least 2 families were using the valley for grazing livestock and harvesting *Polylepis* for firewood. There was clear evidence of ongoing timber removal along the lower edges of the forest, but the impacts seemed minimal, given the size of the overall tract. Large tracts of *Polylepis* that are much closer to populated areas, such as Site D (Fig. 1, Table 1) should be further examined for human impacts, as their proximity to human populations may pose a more imminent threat to the habitat quality of the *Polylepis* forest and surrounding habitat matrix (Lloyd & Marsden 2008).

Mining of precious metals in the immediate vicinity of these forests comprises another potential threat to their persistence. The road from Anchicha to Laguna Anantay was passable by 4-wheel-drive vehicles, because it was maintained for access to an active gold mine located farther to the south. The upper part of the Laguna Anantay Valley had recently been subject to gold-prospecting, and a small, inactive copper mine was located between the road and the lower extent of the *Polylepis* forest. Although the mining-related infrastructure directly facilitated our discovery of this avifauna, mining activities pose direct and imminent threats to the ecological health of these unique valleys. In particular, increased human activity associated with the mining could lead to increased rates of forest cutting and burning.

Community-based conservation plans represent the most realistic and sustainable conservation measures for *Polylepis* forest preservation, because the primary threats to the forest are daily subsistence activities of a small number of residents from surrounding areas (Engblom et al. 2002, Fjeldsa 2002b, Lloyd 2008b). The conservation group Asociación Ecosistemas Andinas (ECOAN) has been successful in protecting the *Polylepis* forests in Cusco and northern Apurímac by educating local communities, providing alternative fuel sources that lessen the need to cut forests, initiating reforestation projects, and establishing community-owned forest reserves (Aucca & Ramsay 2005). ECOAN emphasizes the ecological benefits that local communities are likely to gain from reforestation, including sustainable wood supply and moderation of temperature, rainfall, and erosion. The Anchicha area may be an ideal site in which to develop the same type of community-based strategy that has been pursued by the ECOAN elsewhere.

On-ground assessment of additional *Polylepis* patches in the Anchicha area will be an important aspect of future work. This should include determination of habitat quality, presence or absence of *Polylepis* specialists, and estimation of population sizes for globally threatened species. Although large patches are the top priority for future studies and conservation (Lloyd 2008b), the 89 small patches may also play a key role in ecosystem functioning, providing additional resources for specialist species or serving as stepping-stones among large patches (Lloyd & Marsden 2011). Small patches at our study site were in close proximity to larger patches, and all of the *Polylepis*-specialist bird species were detected foraging within small, medium, and large patches.

Additionally, future studies in the Anchicha area should include the wooded habitats along the upper reaches of steep valleys between 3500 and 4000 m elevation, where the vegetation includes *Polylepis*, *Gynoxys*, and other woody plant genera. It is possible that the rare *Polylepis* specialists use these habitats, as evidenced by the recent record of *Cinclodes aricomae* from the department of Junín at 3700 m elevation in semi-humid elfin forest lacking *Polylepis* (Witt & Lane 2009). To the extent that these areas do comprise viable critical habitat, it could expand the available habitat for *Polylepis* specialists by at least an order of magnitude.

The present study and other new distributional data for *Polylepis*-specialist species (e.g. Witt & Lane 2009) draw attention to our limited knowledge of the *Polylepis*-associated fauna, including species considered to be critically endangered. In the face of accelerating habitat destruction and climate change, satellite-based and on-ground exploration of the high Andes should be considered a top priority for conservation. Historically, full exploration of the high Andes has been hampered by the inaccessibility of sites and the inhospitable climate above 4000 m. This study highlights the need for conservation biologists to scrutinize high-resolution satellite imagery as it becomes available. Google Earth provides a powerful free tool that allows biologists with no substantial resources or training to apply remote sensing to conservation problems. In the near future, as more high-resolution images become available, it will be possible to accurately quantify the entire extent of high-Andean *Polylepis* forests.

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