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## Genome Resources

# De novo assembly of a chromosome-level reference genome for the California Scrub-Jay, *Aphelocoma californica*

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## Abstract

We announce the assembly of the first de novo reference genome for the California Scrub-Jay (*Aphelocoma californica*). The genus *Aphelocoma* comprises four currently recognized species including many locally adapted populations across Mesoamerica and North America. Intensive study of *Aphelocoma* has revealed novel insights into the evolutionary mechanisms driving diversification in natural systems. Additional insights into the evolutionary history of this group will require continued development of high-quality, publicly available genomic resources. We extracted high molecular weight genomic DNA from a female California Scrub-Jay from northern California and generated PacBio HiFi long-read data and Omni-C chromatin conformation capture data. We used these data to generate a de novo partially phased diploid genome assembly, consisting of two pseudo-haplotypes, and scaffolded them using inferred physical proximity information from the Omni-C data. The more complete pseudo-haplotype assembly (arbitrarily designated “Haplotype 1”) is 1.35 Gb in total length, highly contiguous (contig N50 = 11.53 Mb), and highly complete (BUSCO completeness score = 97%), with comparable scaffold sizes to chromosome-level avian reference genomes (scaffold N50 = 66.14 Mb). Our California Scrub-Jay assembly is highly syntenic with the New Caledonian Crow reference genome despite ~10 million years of divergence, highlighting the temporal stability of the avian genome. This high-quality reference genome represents a leap forward in publicly available genomic resources for *Aphelocoma*, and the family Corvidae more broadly. Future work using *Aphelocoma* as a model for understanding the evolutionary forces generating and maintaining biodiversity across phylogenetic scales can now benefit from a highly contiguous, in-group reference genome.

**Key words:** California Conservation Genomics Project, CCGP, long-read sequencing, N50, Omni-C, PacBio

## Introduction

The scrub-jays (genus *Aphelocoma*) are part of a broader clade of jays that radiated in the Americas, which includes other iconic North American species like the Blue Jay (*Cyanocitta cristata*) and the Steller’s Jay (*Cyanocitta stelleri*). Beyond their charm to backyard birdwatchers, these “American jays” have also emerged as a model system for studying the mechanisms driving and maintaining phenotypic and genetic variation across complex landscapes (McCormack et al. 2011; DeRaad et al. 2019; Venkatraman et al. 2019; Cicero

et al. 2022; DeRaad et al. 2022), the evolution of cooperative behavior (Brown 1974; Peterson and Burt 1992; Berg et al. 2012), vocal repertoires (Rosa et al. 2016), and ecological differentiation (Rice et al. 2003; McCormack et al. 2008). The scrub-jays offer a particularly compelling system for studying speciation genomics because the species complex is distributed across North America and is composed of seven discrete, parapatric lineages with varying levels of genetic divergence (DeRaad et al. 2022). These discrete lineages allow for multiple comparisons of different stages in the speciation

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process within a single species complex, making this group an important target for future studies seeking to reconstruct and understand the generation of biodiversity.

The scrub-jays also provide a textbook example of ecological specialization (Pitelka 1951), which is of particular interest for understanding speciation and adaptation. Specifically, the large, hooked bills of the California and Island scrub-jays are ideal for prying open acorns of oak (*Quercus*) species, while the thin, straight, tweezer-like bill of the closely related Woodhouse's Scrub-Jay (*Aphelocoma woodhouseii*) is adapted for removing seeds from pinyon pine (genus *Pinus*) cones (Peterson 1993; Bardwell et al. 2001). These ecologically and genetically divergent species have a narrow zone of secondary contact in eastern California and western Nevada, where moderate rates of hybridization have been documented (Gowen et al. 2014; Vinciguerra et al. 2019). The reticulate evolution in this system offers great potential to increase our understanding of the role of ecological adaptation in both the generation and maintenance of biodiversity, but this effort will require extensive genomic resources.

Additionally, the conservation genetics of two isolated and range-restricted scrub-jays—the federally threatened Florida Scrub-Jay (*Aphelocoma coerulescens*) and the Island Scrub-Jay (*Aphelocoma insularis*)—have been studied intensively. Cutting-edge genomic research in these species of conservation concern includes intensive pedigree analyses of Florida Scrub-Jays (Chen et al. 2016; Aguillon et al. 2017) and an investigation of the genomic signatures of ecological adaptation at microgeographic scales in Island Scrub-Jays (Cheek et al. 2022). This ever-growing wealth of fruitful research into the evolutionary history of the scrub-jay species complex relies on shared genomic resources, which to this point have been limited to a single, scaffold-level reference genome assembly of the Florida Scrub-Jay (NCBI BioSample SAMN12253992; Feng et al. 2020). Here, we present the first de novo genome

assembly for the California Scrub-Jay (NCBI BioSample SAMN31837216) as part of the California Conservation Genomics Project (CCGP; Shaffer et al. 2022; Toffelmier et al. 2022).

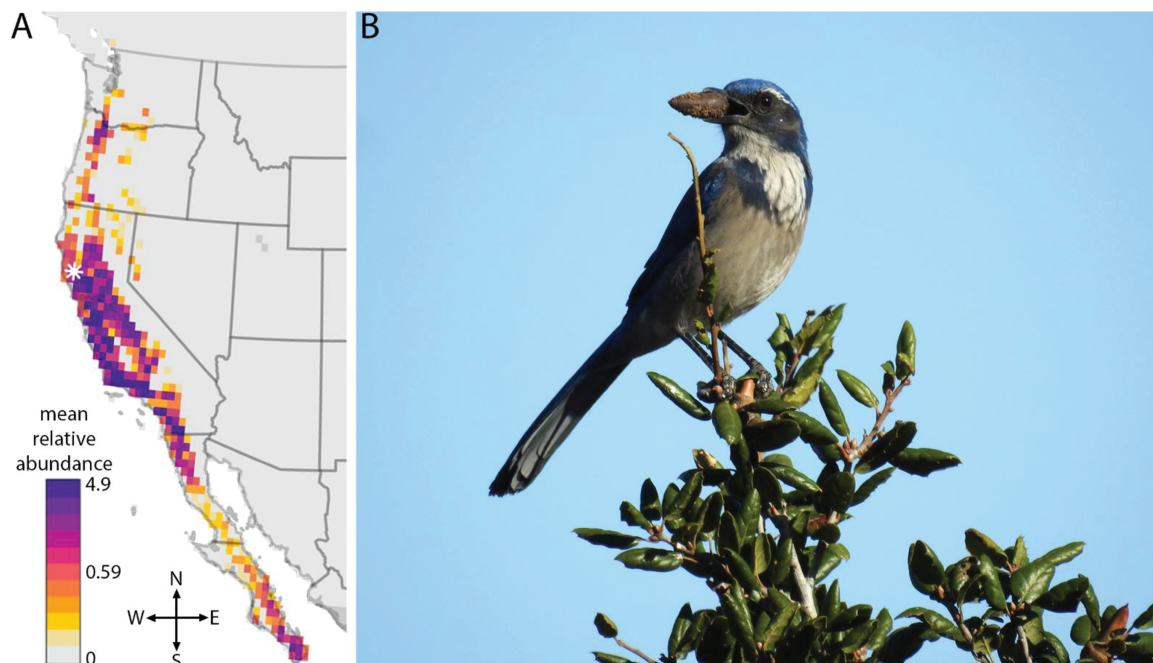
## Methods

### Generating a range map

We used the R package ebirdst (Strimas-Mackey et al. 2021) to download and process observational occurrence data for the California Scrub-Jay from the year 2020. Because the California Scrub-Jay is nonmigratory, the database does not discriminate between breeding and wintering observations, and year-round occurrence points were used to visualize the species' distribution. We downloaded mean relative abundance at a medium resolution and converted it into quantiles of nonzero values. We plotted these data as a heatmap (Fig. 1) on top of a continental basemap generated using the R packages sf (Pebesma 2018) and rnaturalearth (South 2017).

### Biological materials

We collected an adult female California Scrub-Jay on 12 October 2020 at Cow Mountain Recreation Management Area, Lake County, California (39.10238, -123.07647). The specimen was collected under authorization of the California Department of Fish and Wildlife (permit # SC-458), U. S. Fish and Wildlife Service (permit # MB153526), and the University of California Animal Care and Use Committee (protocol # AUP-2015-10-8045-1). This vouchered specimen is deposited at the Museum of Vertebrate Zoology, University of California, Berkeley (MVZ:Bird:193978; <https://arctos.database.museum/guid/MVZ:Bird:193978>). DNA extractions for both HiFi and Omni-C sequencing were performed using flash frozen liver tissue.



**Fig. 1.** A) Mean relative abundance of California Scrub-Jays throughout North America, i.e. the average number of birds seen by an individual observer performing a traveling count at an optimal time of day. Sampling locality of the individual used to generate this reference genome is denoted with a white asterisk. B) California Scrub-Jay (*Aphelocoma californica*) photographed at Occidental College, Los Angeles, CA by John McCormack.

### High molecular weight DNA extraction

Flash frozen liver (20 mg) was homogenized in 2 mL of homogenization buffer (10 mM Tris-HCl pH 8.0 and 25 mM Ethylenediaminetetraacetic acid, i.e., EDTA) using TissueRuptor II (Qiagen, Germany; Cat. # 9002755). In total, 2 mL of lysis buffer (10 mM Tris, 25 mM EDTA, 200 mM NaCl, and 1% Sodium Dodecyl Sulfate, i.e., SDS) and proteinase K (100 µg/mL) were added to the homogenate and incubated overnight at room temperature. Lysate was treated with RNase A (20 µg/mL) at 37 °C for 30 min and was cleaned with equal volumes of phenol/chloroform using phase-lock gels (Quantabio, Beverly, Massachusetts; Cat. # 2302830). The DNA was precipitated by adding 0.4× volume of 5 M ammonium acetate and 3× volume of ice-cold ethanol. The DNA pellet was washed twice with 70% ethanol and resuspended in an elution buffer (10 mM Tris, pH 8.0). We assessed the purity of genomic DNA (gDNA) using a NanoDrop ND-1000 spectrophotometer and recovered a 260/280 ratio of 1.82 and a 260/230 ratio of 2.02. The DNA was quantified by a Qubit 2.0 Fluorometer (Thermo Fisher Scientific, Massachusetts), and a total yield of 50 µg was obtained. The integrity of the high molecular weight (HMW) gDNA was verified on a Femto pulse system (Agilent Technologies, Santa Clara, California), where a majority of DNA was observed in fragments above 125 kb or more.

### HiFi library prep and sequencing

The HiFi SMRTbell library was constructed using the SMRTbell Express Template Prep Kit v2.0 (Pacific Biosciences—PacBio, Cat. #100-938-900) according to the manufacturer's instructions. HMW gDNA was sheared to a target DNA size distribution between 15 and 18 kb. The sheared gDNA was concentrated using 0.45× of AMPure PB beads (PacBio, Menlo Park, California; Cat. #100-265-900) for the removal of single-strand overhangs at 37 °C for 15 min, followed by further enzymatic steps of DNA damage repair at 37 °C for 30 min end repair and A-tailing at 20 °C for 10 min and 65 °C for 30 min, and ligation of overhang adapter v3 at 20 °C for 60 min. The SMRTbell library was purified and concentrated with 1× AMPure PB beads (PacBio, Cat. #100-265-900) for nuclease treatment at 37 °C for 30 min and size selection using the BluePippin/PippinHT system (Sage Science, Beverly, Massachusetts; Cat. #BLF7510/HPE7510) to collect fragments greater than 7 to 9 kb. The 15 to 20 kb average HiFi SMRTbell library was sequenced at the UC Davis DNA Technologies Core (Davis, California) using two 8M SMRT cells, Sequel II sequencing chemistry 2.0, and 30-h movies each on a PacBio Sequel II sequencer.

### Omni-C library prep and sequencing

The Omni-C library was prepared using the Dovetail Omni-C Kit (Dovetail Genomics, Scotts Valley, California) according to the manufacturer's protocol with slight modifications. First, liver tissue was thoroughly ground with a mortar and pestle while cooled with liquid nitrogen. Subsequently, chromatin was fixed in place in the nucleus. The suspended chromatin solution was then passed through 100 and 40 µm cell strainers to remove large debris. Fixed chromatin was digested under various conditions of DNase I until a suitable fragment length distribution of DNA molecules was obtained. Chromatin ends were repaired and ligated to a biotinylated bridge adapter followed by proximity ligation of adapter

containing ends. After proximity ligation, crosslinks were reversed, and the DNA was purified from proteins. Purified DNA was treated to remove biotin that was not internal to ligated fragments. An NGS library was generated using an NEB Ultra II DNA Library Prep kit (New England Biolabs—NEB, Ipswich, Massachusetts) with an Illumina compatible y-adaptor. Biotin-containing fragments were then captured using streptavidin beads. The post-capture product was split into two replicates prior to PCR enrichment to preserve library complexity, with each replicate receiving unique dual indices. The library was sequenced at Vincent J. Coates Genomics Sequencing Lab (Berkeley, California) across two separate flow cells on an Illumina NovaSeq platform (Illumina, San Diego, California) generating 150 basepair paired-end reads.

### Genome assembly

We assembled the genome of the California Scrub-Jay following the CCGP assembly pipeline Version 6.0 (Table 1 lists the tools and nondefault parameters used in the assembly). The pipeline uses PacBio HiFi reads and Omni-C data to produce a high-quality, highly contiguous genome assembly, with heterozygous regions assigned arbitrarily to one of two pseudo-haplotypes. First, we removed the remnant adapter sequences from the PacBio HiFi dataset using HiFiAdapterFilt (Sim et al. 2022) and generated the initial dual or partially phased diploid assembly (<http://lh3.github.io/2021/10/10/introducing-dual-assembly>) using HiFiasm (Cheng et al. 2022) on Hi-C mode, with the filtered PacBio HiFi reads and the Omni-C dataset. We then aligned the Omni-C data to each pseudo-haplotype following the Arima Genomics Mapping Pipeline ([https://github.com/ArimaGenomics/mapping\\_pipeline](https://github.com/ArimaGenomics/mapping_pipeline)) and then scaffolded them with SALSA (Ghurye et al. 2017, 2019).

The pseudo-haplotypes were manually curated by iteratively generating and analyzing their corresponding Omni-C contact maps. To generate the contact maps, we aligned the Omni-C data with BWA-MEM (Li 2013), identified ligation junctions, and generated Omni-C pairs using pairtools (Goloborodko et al. 2018). We generated a multiresolution Omni-C matrix with cooler (Abdennur and Mirny 2020) and balanced it with hicExplorer (Ramírez et al. 2018). We used HiGlass (Kerpedjiev et al. 2018) and the PretextSuite (<https://github.com/wtsi-hpag/PretextView>; <https://github.com/wtsi-hpag/PretextView>; <https://github.com/wtsi-hpag/PretextView>) to visualize the contact maps where we identified mis-assemblies and mis-joins, and finally modified the assemblies using the Rapid Curation pipeline from the Wellcome Trust Sanger Institute, Genome Reference Informatics Team (<https://gitlab.com/wtsi-grit/rapid-curation>). Some of the remaining gaps (joins generated during scaffolding and curation) were closed using the PacBio HiFi reads and YAGCloser (<https://github.com/merlyescalona/yagcloser>). Finally, we checked for contamination using the BlobToolKit Framework (Challis et al. 2020).

### Mitochondrial genome assembly

We assembled the mitochondrial (mtDNA) genome of *A. californica* from the PacBio HiFi reads using the reference-guided pipeline MitoHiFi (Allio et al. 2020; Uliano-Silva et al. 2021). The mtDNA genome of *A. coerulescens* (NCBI:NC\_051467.1; Feng et al. 2020; B10K Project Consortium) was used as the starting sequence. After completion of the nuclear genome, we searched for matches of

**Table 1.** Software used for all the analyses presented in the paper with their corresponding version and nondefault parameters.

Purpose	Software and options <sup>a</sup>	Version
Generating the range map		
Processing of observational occurrence data	ebirdst	1.2020.1
Map plotting with occurrence data	sf	1.0-7
	rnaturalearth	0.1.0
Assembly		
Filtering PacBio HiFi adapters	HiFiAdapterFilt	Commit 64d1c7b
K-mer counting	Meryl (k = 21)	1
Estimation of genome size and heterozygosity	GenomeScope	2
De novo assembly (contigging)	HiFiasm (Hi-C mode, --primary, output p_ctg.hap1, p_ctg.hap2)	0.16.1-r375
Scaffolding		
Omni-C data alignment	Arima Genomics Mapping Pipeline	Commit 2e74ea4
Omni-C scaffolding	SALSA (-DNASE, -i 20, -p yes)	2
Gap closing	YAGCloser (-mins 2 -f 20 -mcc 2 -prt 0.25 -cft 0.2 -pld 0.2)	Commit 0e34c3b
Omni-C contact map generation		
Short-read alignment	BWA-MEM (-5SP)	0.7.17-r1188
SAM/BAM processing	samtools	1.11
SAM/BAM filtering	pairtools	0.3.0
Pairs indexing	pairix	0.3.7
Matrix generation	cooler	0.8.10
Matrix balancing	hicExplorer (hicCorrectmatrix correct --filterThreshold -2 4)	3.6
Contact map visualization	HiGlass	2.1.11
	PretextMap	0.1.4
	PretextView	0.1.5
	PretextSnapshot	0.0.3
Manual curation tools	Rapid curation pipeline (Wellcome Trust Sanger Institute, Genome Reference Informatics Team)	Commit 4ddca450
Genome quality assessment		
Basic assembly metrics	QUAST (--est-ref-size)	5.0.2
Assembly completeness	BUSCO (-m geno, -l aves)	5.0.0
	Merqury	2020-01-29
Circos Assembly Consistency (Jupiter) plot	JupiterPlot (ng = 95, m = 5000000)	1.0
Identification of repetitive elements	RepeatMasker	4.0.5
Organelle assembly		
Mitogenome assembly	MitoHiFi (-r, -p 50, -o 1)	2 Commit c06ed3e
Contamination screening		
Local alignment tool	BLAST+ (-db nt, -outfmt "6 qseqid staxids bitscore std," -max_target_seqs 1, -max_hsps 1, -evaluate 1e-25)	2.1
General contamination screening	BlobToolKit	2.3.3

Citations for the software used are detailed in the text.

<sup>a</sup>Options detailed for nondefault parameters.

the resulting mitochondrial assembly sequence in the nuclear genome assembly using BLAST+ (Camacho et al. 2009) and filtered out contigs and scaffolds from the nuclear genome with a percentage of sequence identity >99% and size smaller than the mtDNA assembly sequence.

### Evaluating the assembly

We generated k-mer counts from the PacBio HiFi reads using meryl (<https://github.com/marbl/meryl>). The k-mer counts were then used in GenomeScope2.0 (Ranallo-Benavidez et al. 2020) to estimate genome features including genome size, heterozygosity, and repeat content. We ran QUAST

(Gurevich et al. 2013) to obtain general contiguity metrics. To evaluate genome quality and functional completeness, we used BUSCO (Manni et al. 2021) with the Aves ortholog database (aves\_odb10) which contains 8,338 genes. Assessment of base level accuracy (QV) and k-mer completeness was performed using the previously generated meryl database and merqury (Rhie et al. 2020). We further estimated genome assembly accuracy via BUSCO gene set frameshift analysis using the pipeline described in Korf et al. (2017). Measurements of the size of the phased blocks are based on the size of the contigs generated by HiFiasm on HiC mode. We follow the quality metric nomenclature established by

Rhie et al. (2021), with the genome quality code  $x \cdot y \cdot P \cdot Q \cdot C$ , where  $x = \log_{10}[\text{contig NG50}]$ ;  $y = \log_{10}[\text{scaffold NG50}]$ ;  $P = \log_{10}[\text{phased block NG50}]$ ;  $Q = \text{Phred base accuracy QV}$  (quality value);  $C = \% \text{ genome represented by the first "n" scaffolds, following a karyotype of } 2n = 80 \text{ estimated as the median number of chromosomes from other species in the same family (Genome on a Tree—GoaT; tax\_tree(28725))}$ . Quality metrics for the notation were calculated on the assembly for Haplotype 1.

We used RepeatMasker (Chen 2004) to identify repetitive elements throughout the assembly using a transposable element (TE) library generated from de novo repeat annotation of the closely related Steller's Jay (*C. stelleri*) reference genome (Benham et al. 2023). We used the output from RepeatMasker as input for the included perl script "calcDivergenceFromAlign.pl" to classify repetitive regions into "families" of transposable elements. We generated visualizations of repetitive content across the genome and between assemblies using the R package (R Core Team 2019) *ggplot2* (Wickham et al. 2020).

We then used the program *Jupiter Plot* (Chu 2018) to map the scaffolds of our pseudo-haplotype genome assemblies to each other to compare relative synteny and completeness. We repeated this procedure for additional pairwise comparisons between Haplotype 1 of our assembly and the chromosomally scaffolded New Caledonian Crow (*Corvus moneduloides*; NCBI BioSample SAMN12368441; [https://www.ncbi.nlm.nih.gov/assembly/GCF\\_009650955.1/](https://www.ncbi.nlm.nih.gov/assembly/GCF_009650955.1/); Rhie et al. 2021) and the Florida Scrub-Jay reference genome (*A. coerulescens*; NCBI BioSample SAMN12253992; [https://www.ncbi.nlm.nih.gov/assembly/GCA\\_013398375.1/](https://www.ncbi.nlm.nih.gov/assembly/GCA_013398375.1/); Feng et al. 2020). In all comparisons, we included only scaffolds >5 Mb from the genome used as the reference genome (i.e. the left side of each plot). For the comparison with the New Caledonian Crow and the comparison between our two pseudo-haplotype assemblies, we also specified that only the largest scaffolds making up 95% of the mapped genome assembly (i.e. the right side of each plot) should be used for visualization.

## Results

### Sequence data

The Omni-C and PacBio HiFi sequencing libraries generated 360.02 million read pairs and 5.01 million reads, respectively. The latter yielded 51.4-fold coverage (N50 read length 12,728 bp; minimum read length 89 bp; mean read length 12,578 bp; maximum read length of 51,606 bp) based on the GenomeScope2.0 genome size estimation of 1.23 Gb. Based on PacBio HiFi reads, we estimated 0.139% sequencing error rate and 0.663% nucleotide heterozygosity rate. The k-mer spectrum based on PacBio HiFi reads recovers a bimodal distribution with two major peaks at ~13 and ~26 (Fig. 2A), where peaks correspond to heterozygous and homozygous states of a diploid species.

### Genome assembly

The final assembly (bAphCal1) consists of two pseudo-haplotypes, both with assembly sizes similar to the estimated value from GenomeScope2.0 (Fig. 2A, Pflug et al. 2020). Haplotype 1 assembly consists of 1,393 scaffolds spanning 1.35 Gb with a contig N50 of 11.53 Mb, scaffold N50 of 66.14 Mb, longest contig spanning 77.93 Mb, and largest

scaffold spanning 158.41 Mb. The Haplotype 2 assembly consists of 1,631 scaffolds spanning 1.19 Gb with a contig N50 of 11.67 Mb, scaffold N50 of 65.72 Mb, largest contig spanning 52.3 Mb, and largest scaffold spanning 160.92 Mb. Detailed assembly statistics are reported in Table 2, and a graphical representation for the Haplotype 1 assembly is depicted in Fig. 2B. The Haplotype 1 assembly has a BUSCO completeness score of 97% using the Aves gene set, a per-base quality (QV) of 45.89, a k-mer completeness of 92.49, and a frameshift indel QV of 41.16; the Haplotype 2 assembly has a BUSCO completeness score of 93.3% using the same BUSCO gene set, a per-base quality (QV) of 48.23, a k-mer completeness of 85.91, and a frameshift indel QV of 41.16.

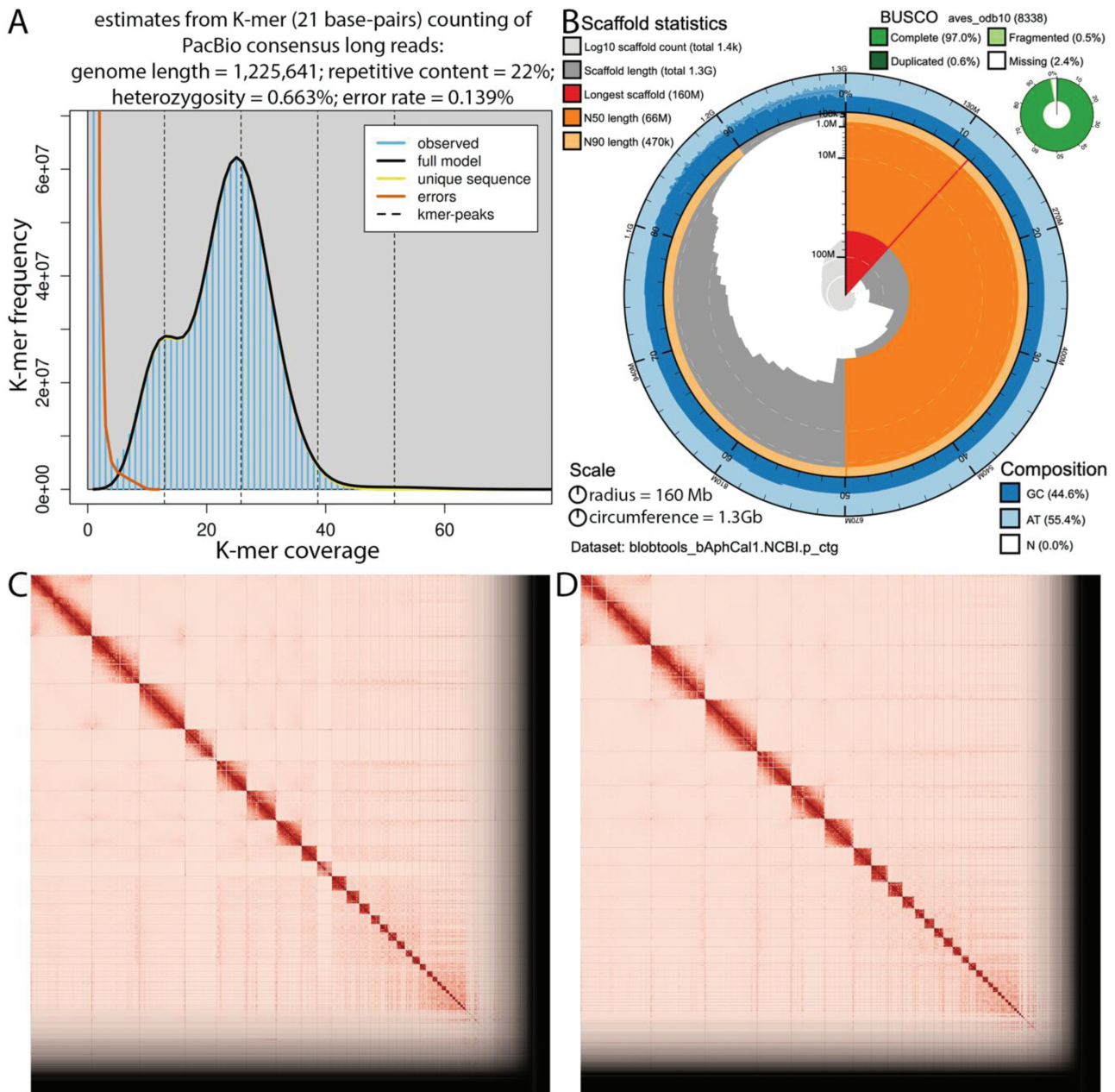
During manual curation, we generated 8 breaks and 71 joins in Haplotype 1 as well as 10 breaks and 54 joins in Haplotype 2. We were able to close a total of 13 gaps, 7 in the Haplotype 1 assembly and 6 in the Haplotype 2 assembly. Finally, we filtered out five contigs from Haplotype 2, four corresponding to Arthropod and Bacillota contaminants and one corresponding to mitochondrial contamination. No further contigs were removed. The Omni-C contact maps show that both pseudo-haplotype assemblies are highly contiguous (Fig. 2C and D; both assemblies are available on NCBI, see Data availability for details). We separately assembled a mtDNA genome with MitoHiFi (NCBI sequence JAQMYR010001393.1; <https://www.ncbi.nlm.nih.gov/nuccore/JAQMYR010001393.1/>). The final mtDNA genome size was 18,021 bp. The base composition of the final assembly version was A = 29.35%, C = 21.33%, G = 20.23%, T = 29.08%, and the mtDNA genome assembly includes 10 unique transfer RNAs.

### Comparing our partially phased pseudo-haplotype assemblies

Syntenic mapping revealed overall synteny between our two phased pseudo-haplotype assemblies (here and on NCBI, these two assemblies are consistently, but arbitrarily, designated Haplotypes 1 and 2; Fig. 3A). Notably, synteny mapping indicates that both sex-linked scaffolds (i.e. scaffolds corresponding to the Z and W chromosomes in the New Caledonian Crow genome assembly) are present in the Haplotype 1 assembly and absent from the Haplotype 2 assembly. The Haplotype 2 assembly exhibited both a smaller assembly size and a reduced proportion of repetitive elements (Fig. 3B), likely because of this lack of sex chromosome scaffolds, which are enriched for repetitive elements in birds (Davis et al. 2010). Across both pseudo-haplotype assemblies, three classes of repetitive elements dominate the repetitive landscape: long interspersed nuclear elements (LINEs), long terminal repeat retrotransposons (LTRs), and satellite DNA (Fig. 3C). The most frequent repetitive element class (LTRs) spans >8% of the Haplotype 1 assembly and >6% of the Haplotype 2 assembly.

### Comparing our "Haplotype 1" assembly to other Corvid assemblies

Syntenic mapping reveals strong overall synteny between the chromosome-level reference genome for the New Caledonian Crow and Haplotype 1 of our de novo assembled reference genome for the California Scrub-Jay (Fig. 4A). This synteny comparison also highlights the overall contiguity of our Haplotype 1 assembly, with all visualized



**Fig. 2.** Visual overview of genome assembly metrics. A) K-mer spectra output generated from PacBio HiFi data without adapters using GenomeScope2.0, which indicates low (<1%) heterozygosity. The lower shoulder of the distribution corresponds to haplotype-specific K-mers (i.e. K-mers including a heterozygous site), which should have half the read depth of the taller peak, which corresponds to K-mers shared identically by both haplotypes in the diploid individual we sequenced. B) BlobToolKit Snail plot showing a graphical representation of the quality metrics presented in Table 2 for the *Aphelocoma californica* "Haplotype 1" assembly (bAphCali1.0.hap1). The plot circle represents the full size of the assembly. The red line represents the size of the longest scaffold; all other scaffolds are arranged in size-order moving clockwise around the plot and drawn in gray starting from the outside of the central plot. Dark and light orange arcs show the scaffold N50 and scaffold N90 values. The central light gray spiral shows the cumulative scaffold count with a white line at each order of magnitude. White regions in this area reflect the proportion of Ns in the assembly; the dark versus light blue area around it shows mean, maximum, and minimum GC versus AT content at 0.1% intervals (Challis et al. 2020). Omni-C contact maps for C) Haplotype 1 and D) Haplotype 2 genome assemblies generated with PretextSnapshot. Omni-C contact maps translate proximity of genomic regions in 3D space to contiguous linear organization. Each cell in the contact map corresponds to sequencing data supporting the linkage (or join) between two genomic regions.

chromosome-assigned scaffolds from the New Caledonian Crow genome assembly represented by a single scaffold in our California Scrub-Jay assembly.

Visualizing synteny with the Florida Scrub-Jay reference genome revealed limited evidence for structural rearrangements within the scrub-jay species complex, as expected among closely related avian species (Fig. 4B). This

synteny comparison also highlights the increased contiguity of our assembly compared with the only previously available reference genome for the genus *Aphelocoma*. Specifically, our novel assembly offers a contig N50 nearly two orders of magnitude greater (11.53 Mb versus 134 kb; Table 2) than the current publicly available Florida Scrub-Jay reference genome (Feng et al. 2020).

**Table 2.** Sequencing, assembly statistics, and accession numbers.

BioProjects and Vouchers	CCGP NCBI BioProject		PRJNA720569					
	Genera NCBI BioProject		PRJNA766263					
	Species NCBI BioProject		PRJNA777134					
	NCBI BioSample		SAMN31837216					
	Specimen identification		MVZ:Bird:193978					
	NCBI Genome accessions		Haplotype 1		Haplotype 2			
Assembly accession		GCA_028536675.1		GCA_028536645.1				
Genome sequences		JAQMYR000000000		JAQMYS000000000				
Genome Sequence	PacBio HiFi reads	Run	1 PACBIO_SMRT (Sequel II) run: 5 M spots, 63.1 G bases, 35.3 Gb					
		Accession	SRR23446543					
	Omni-C Illumina reads	Run	2 ILLUMINA (Illumina NovaSeq 6000) run: 360.1 M spots, 108.7 G bases, 36.9 Gb					
		Accession	SRR23446541, SRR23446542					
Genome Assembly Quality Metrics	Assembly identifier (quality code <sup>a</sup> )			bAphCal1(7.7.P7.Q46.C85)				
	HiFi read coverage <sup>b</sup>			51.48×				
				Haplotype 1		Haplotype 2		
	Number of contigs			1,665		1,799		
	Contig N50 (bp)			11,534,525		11,670,509		
	Contig NG50 <sup>b</sup>			13,901,234		11,191,859		
	Longest contigs			77,933,725		52,308,079		
	Number of scaffolds			1,393		1,631		
	Scaffold N50			66,144,195		65,728,546		
	Scaffold NG50 <sup>b</sup>			76,801,313		65,728,546		
	Largest scaffold			158,410,743		160,920,769		
	Size of final assembly			1,348,500,425		1,191,279,315		
	Phased block NG50 <sup>b</sup>			11,313,027		12,152,900		
	Gaps per Gbp (# gaps)			201 (272)		141 (168)		
	Indel QV (frameshift)			41.16		41.16		
	Basepair QV			45.8906		48.2358		
				Full assembly = 46.8365				
	K-mer completeness			92.4996		85.916		
				Full assembly = 99.5694				
	BUSCO completeness (aves_odb10) <i>n</i> = 8,338			C	S	D	F	M
			H1 <sup>c</sup>	97.00%	96.40%	0.60%	0.50%	2.50%
			H2 <sup>c</sup>	93.30%	92.80%	0.50%	0.60%	6.10%
	Organelles		# Partial mitochondrial sequence			JAQMYR010001393.1		

<sup>a</sup>Assembly quality code *x-y-P-Q-C* derived notation, from [Rhie et al. \(2021\)](#). *x* = log<sub>10</sub>[contig NG50]; *y* = log<sub>10</sub>[scaffold NG50]; *P* = log<sub>10</sub>[phased block NG50]; *Q* = Phred base accuracy QV (quality value); *C* = % genome represented by the first “*n*” scaffolds, following a karyotype of 2*n* = 80 for *A. californica*, estimated as the median number of chromosomes from other species in the same family (Genome on a Tree—GoaT; tax\_tree(28725)). Quality code for all the assembly denoted by haplotype 1 assembly (bAphCal1.0.hap1).

<sup>b</sup>Read coverage and NGx statistics have been calculated based on the estimated genome size of 1.225 Gb.

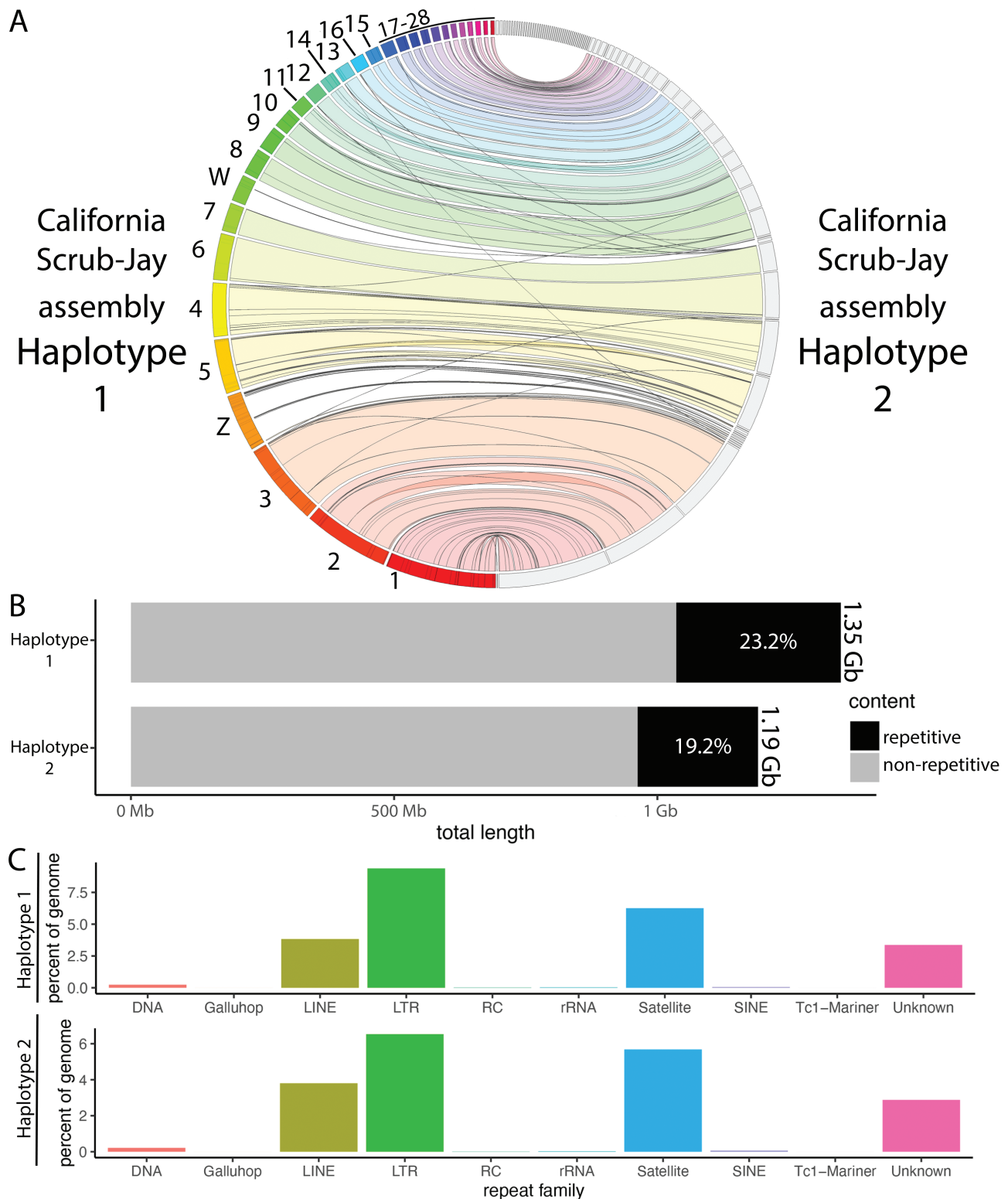
<sup>c</sup>H1: Haplotype 1; H2: Haplotype 2.

## Discussion

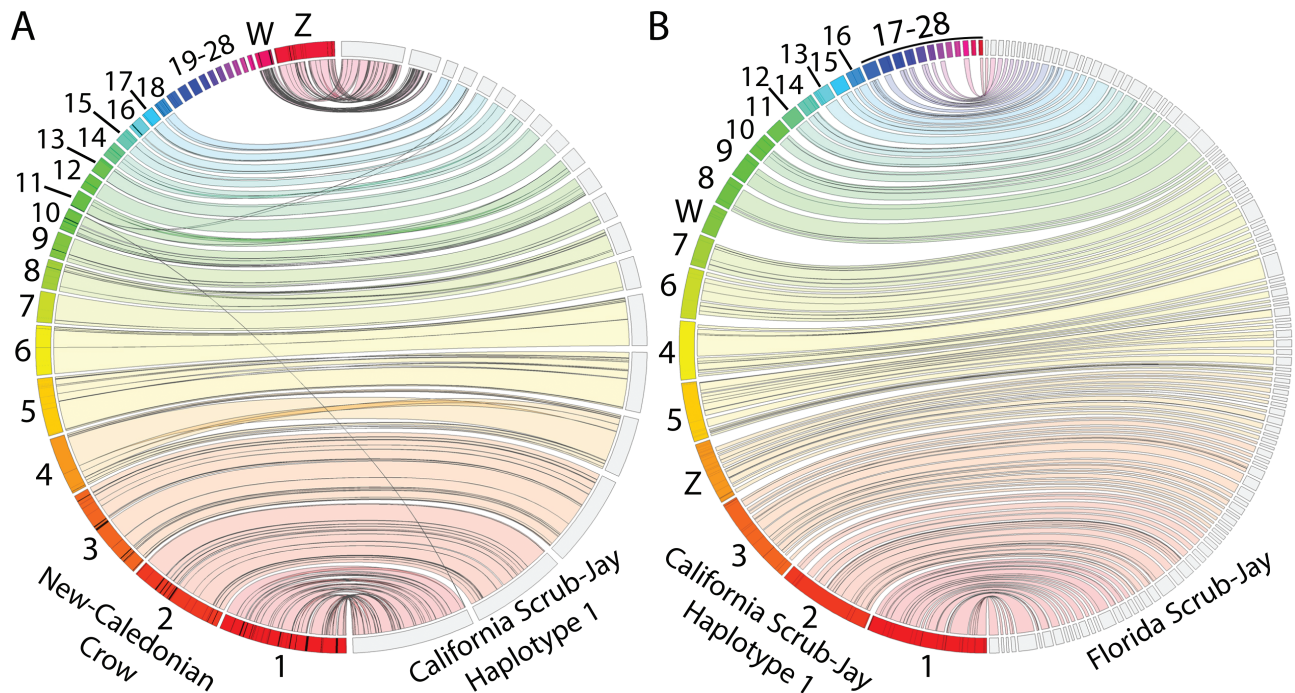
We present the first de novo reference genome assemblies for the California Scrub-Jay (*Aphelocoma californica*). We used state-of-the-art approaches for long-read sequencing

(PacBio HiFi) and chromatin conformation capture (Dovetail Omni-C) to generate a highly contiguous and complete reference genome that reaches the threshold for “gold quality” avian genome assemblies ([Kapusta and Suh 2017](#)). The ~11.5





**Fig. 3.** Comparison of the two pseudo-haplotype assemblies. A) Jupiter plot displaying the synteny between the two assemblies. Scaffolds on the left are ordered by size and labeled based on synteny with the chromosomally assembled New Caledonian Crow reference genome. Note that scaffolds without matches on the top of the plot are due to a limit in the number of comparisons that can be drawn with the *Jupiter Plot* software, not necessarily a lack of syntenic matches. Meanwhile scaffolds in the middle of the assembly without a match (e.g., chromosomes Z and W), reflect a real lack of a syntenic match between assemblies. B) Bar plot comparing the genome size and proportion of repetitive content between the two pseudo-haplotype assemblies. C) Bar plots show the proportion of the genome spanned by each repeat family for each assembly.



**Fig. 4.** Assessing synteny between publicly available reference genomes from the avian family Corvidae. A) Jupiter plot visually displaying synteny between our “Haplotype 1” California Scrub-Jay genome assembly and the chromosomally assembled New Caledonian Crow reference genome. B) Jupiter plot mapping the scaffolds of a reference assembly for the closely related Florida Scrub-Jay to our “Haplotype 1” assembly. Scaffolds in our Haplotype 1 assembly are labeled as in Fig. 3A. The lack of homology with the W chromosome in our assembly was expected because a male (lacking the W chromosome) individual was sequenced to generate the Florida Scrub-Jay assembly.

Mb contig N50 of both assemblies (primary and alternate) places them within the top 10% (top 100 overall) of all publicly available avian reference genomes in terms of contiguity (as of 13 February 2023; referenced from <https://www.ncbi.nlm.nih.gov/data-hub/genome/?taxon=8782>). Meanwhile, the BUSCO scores for our Haplotype 1 and 2 assemblies (97% and 93.3% of avian genes fully present, respectively) indicate that a large proportion of conserved avian genes can be found in their complete states in both assemblies. The exceptional completeness and contiguity statistics of these assemblies indicate that they will serve as an important public resource for investigators seeking to understand the genomics and evolutionary history of the scrub-jays and their allies, and more generally all birds, for years to come.

#### Assessing the genome size and repetitive content of the California Scrub-Jay

The two pseudo-haplotype assemblies we present here differ in overall genome size (1.35 and 1.19 Gb for the Haplotype 1 and 2 assemblies, respectively), flanking the 1.23 Gb kmer-based genome size estimate. Synteny mapping between these assemblies clearly reveals that scaffolds corresponding to both avian sex chromosomes (Z and W) are present in Haplotype 1 but absent in Haplotype 2. The missing sex chromosome scaffolds in the Haplotype 2 assembly are an artifact of the pseudo-haplotype approach, reflecting the fact that both of these chromosomes (W and Z) are present only in a single copy in individuals of the heterogametic sex, and by chance, each of these hemizygous copies was assigned to the Haplotype 1 assembly. This difference explains the gaps in both overall assembly size and repetitive content between our two pseudo-haplotype assemblies. We encourage

investigators interested in a California Scrub-Jay reference genome assembly to use the Haplotype 1 assembly (GenBank assembly accession: GCA\_028536675.1) if they wish to perform analyses involving sex chromosomes.

Notably, our pseudo-haplotype assemblies represent the largest assembled reference genomes to date from the avian family Corvidae (as of 17 March 2023; accessed from: <https://www.ncbi.nlm.nih.gov/assembly/?term=corvidae>). This unusually large genome size in *A. californica* appears to result from an expansion in repetitive elements, specifically LINES, LTRs, and satellite DNA compared with other Corvid genomes (Benham et al. 2023). While assessing genome size across different assembly approaches is difficult (Barrière et al. 2009), our large genome assembly size is bolstered by previous genome size estimates based on *c*-values, which indicated that the *A. coerulescens* likely has the largest genome among Corvids (Andrews et al. 2009). Together, these lines of evidence tentatively support an increased genome size in the genus *Aphelocoma*, that may have been driven by an expansion in repetitive elements in this lineage. As more high-quality avian reference genomes with accurate size estimations become publicly available, our understanding of the evolution of avian genome size will continue to increase.

#### Assessing synteny across the avian family Corvidae

Our results add support to the well-documented evidence for extensive synteny across the avian genome (Ellegren 2010), but also provide evidence for some small structural rearrangements between the California Scrub-Jay and the New Caledonian Crow (estimated split ~10 MYA; McCullough et al. 2022). Meanwhile, there is very little visual

evidence for structural rearrangements between California and Florida scrub-jays (estimated split ~5 MYA; McCormack et al. 2011), although the differing contiguity between these assemblies makes it difficult to conclude with confidence that we are not missing rearrangements split between scaffolds. Overall, it is difficult to determine whether the mismatches in these synteny plots result from real structural rearrangements or whether they are technical artifacts from the difficult and variable process of de novo genome assembly. Future work using high-quality de novo assemblies for all scrub-jay species will be necessary to better understand the prevalence and evolutionary implications of structural variation among this species complex (e.g. Höök et al. 2023).

## Conclusions

We generated a high-quality de novo reference genome assembly for the California Scrub-Jay, with two phased pseudo-haplotype assemblies made publicly available via NCBI (PRJNA9044314 and PRJNA9044313). This expands the number of taxa within *Aphelocoma* for which a de novo reference genome assembly has been generated and sets a new bar for contiguity among *Aphelocoma* reference genomes. Future studies of the genus *Aphelocoma* will now be able to use this chromosome-level reference genome for mapping genomic sequence data. This will increase the genomic resolution of any future investigations aimed at identifying the genomic regions associated with environmental adaptation, genetic incompatibilities, or adaptive trait divergence (e.g. Aguillon et al. 2021) among the scrub-jays. Future comparative studies will also be able to leverage this assembly to assess evolutionary constraints on genome size and repetitive content across corvids and beyond. Overall, this de novo assembly represents a crucial addition to the pool of shared genomic resources for the highly studied scrub-jay species complex, which is rapidly developing as a natural model system for understanding how evolutionary forces shape patterns of extant biodiversity.

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## Data availability

The assembled reference genomes presented here have been made immediately publicly available at: NCBI BioProject PRJNA904314 (Pseudo-haplotype 1; <https://www.ncbi.nlm.nih.gov/bioproject/PRJNA904314/>) and NCBI BioProject PRJNA904313 (Pseudo-haplotype 2; <https://www.ncbi.nlm.nih.gov/bioproject/PRJNA904313/>). All raw sequence data generated here are also immediately publicly available via NCBI, including PacBio sequence data (accession: SRX19355857; [https://trace.ncbi.nlm.nih.gov/Traces/?view=run\\_browser&acc=SRR23446543&display=metadata](https://trace.ncbi.nlm.nih.gov/Traces/?view=run_browser&acc=SRR23446543&display=metadata)), OmniC data from NovaSeq flow cell 1 (accession: SRX19355858; <https://www.ncbi.nlm.nih.gov/sra/SRX19355858>), and flow cell 2 (accession: SRX19355859; <https://www.ncbi.nlm.nih.gov/sra/SRX19355859>). Assembly scripts and other data for the analyses presented can be found at the following GitHub repository: [www.github.com/ccgproject/ccgp\\_assembly](http://www.github.com/ccgproject/ccgp_assembly).

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