A Phased, Chromosome-scale Genome for *Malus domestica* 'WA 38'

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Abstract

Genome sequencing for agriculturally important Rosaceous crops has made rapid progress both in completeness and annotation quality. Whole genome sequence and annotation gives breeders, researchers, and growers information about cultivar specific traits such as fruit quality, disease resistance, and informs strategies to enhance postharvest storage. Here we present a haplotype-phased, chromosomal level, genome of *Malus domestica*, 'WA 38', a new cultivar of apple released to market in 2017 as Cosmic Crisp ®. Using both short and long read sequencing our fully phased genome of 'WA 38' is about 650 Megabases, with a BUSCO score of 98.7% complete. The genome contains two haplomes (HapA and HapB) which are composed of 17 chromosomes each. A total of 48,227 and 54,479 genes were annotated from HapA and HapB, respectively. Additionally, we provide genome-scale comparisons to 'Gala', 'Honeycrisp', and other relevant cultivars highlighting major structural and quality differences. This assembly and annotation was done in collaboration with the American Campus Tree Genomes project that included 'WA 38' (WSU) and the 'd'Anjou' pear (Auburn University). To ensure transparency, reproducibility, and applicability for any genome project, our genome assembly and annotation workflow is recorded in detail and shared under a public GitHub repository. All software is containerized, offering a simple implementation of the workflow.

Keywords

Apple genomics, *Malus domestica* 'WA 38', genome sequence, comparative genomics, plant genomics, phased assembly, genome annotation

Background

For economically important crop species, having full-resolution reference genomes aids in the understanding of traits associated with commodity quality, disease resistance, long-term storage, and shelf life. Apple (*Malus domestica*) is the number one consumed fruit in the United States, with a Farm-Gate Revenue of $3.2 billion in the U.S.[1], and $78 billion globally[2]. There are over 7,000 apple varieties grown world wide[3], each with unique colors, flavors, and textures[4]. Therefore, a single genome is unlikely to capture the complexity of all cultivars within this highly heterozygous species (H. Zhang et al. 2022; W. Li et al. 2022). One such cultivar is 'WA 38', commercially released as Cosmic Crisp® in 2017 by the Pome Fruit Breeding Program at Washington State University's (WSU) Tree Fruit Research and Extension Center (Figure 1). 'WA 38' is a cross between 'Honeycrisp' and 'Enterprise', made using classical breeding methods in 1997. One parent, 'Honeycrisp', is well-known for its crisp texture, firmness retention in storage, disease resistance, and cold hardiness, but is highly susceptible to production and postharvest issues (Khan et al. 2022). The other parent, 'Enterprise', is an easy-to-grow cultivar that has extended postharvest storage capabilities, however it is not widely cultivated commercially due to its less desirable eating quality (Crosby et al. 1994). Their resulting cross has been met with favorable reviews for its appealing color, texture, flavor, cold hardiness, long-term storage capabilities (>1 year), and scab resistance (Evans et al. 2012). However, it inherited undesirable traits as well, such as a propensity for physiological symptoms that may be related to mineral imbalances (Sheick et al. 2023; Sallato, Whiting, and Munguia 2021), maturity at harvest[5], and an 'off' flavor that has been brought up by consumers that may be the result of improper picking times, crop load management, handling/packing practices or other post harvest processes[6]. Most concerning is green spot (Figure 1 C, D, and F), a corking disorder that seems to be unique to 'WA 38', but with etiology similar to disorders associated with mineral imbalances such as bitter pit and drought spot (Sheick et al. 2022, 2023). The propensity for and cause of physiological disorders often differs on a cultivar-by-cultivar basis (Pareek 2019), and a genetic basis for such predispositions is likely (Di Guardo et al. 2013; Lum

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[1] https://usapple.org/industry-at-a-glance
[2] https://fruitgrowersnews.com/news/global-apple-market-reached-78m-set-to-continue-moderate-growth/
[3] https://waapple.org/did-you-know/
[4] Retrieved December 27, 2022, from https://plants.ces.ncsu.edu/plants/malus-domestica/common-name/apples/
[5] https://www.actahort.org/members/showpdf?session=1982017
[6] https://treefruit.wsu.edu/article/2022-update-additional-wa-38-harvest-and-storage-considerations/

et al. 2016; Johnston and Brookfield 2012; Liebhard et al. 2003). Thus, improved resolution of cultivar-specific genomic differences is critical for advancing our understanding of how economically important traits, such as physiological disorders, are inherited and how they can be managed more efficiently.

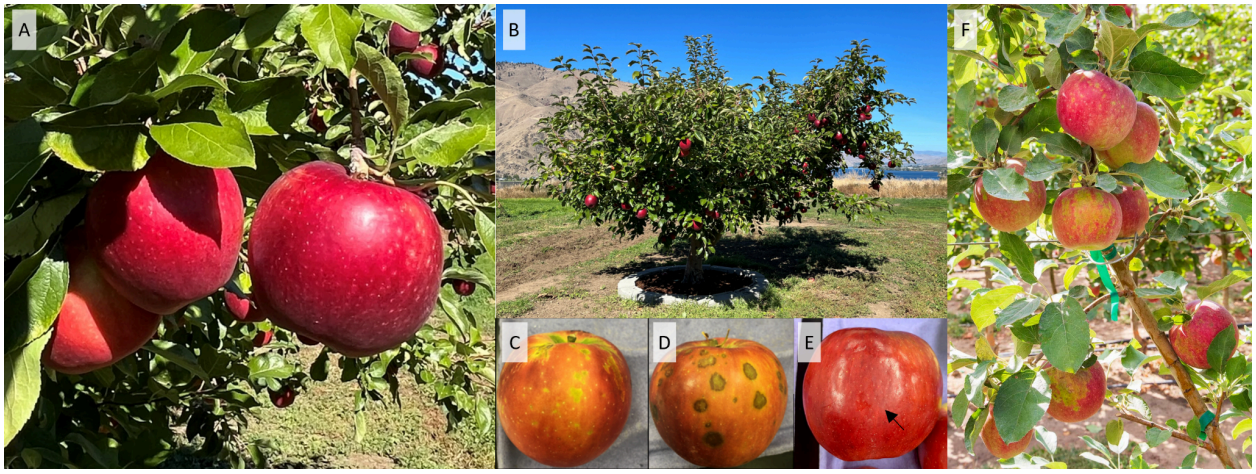

Figure. 1. 'WA 38', a cultivar of apple developed by the Washington State University Apple Breeding Program (a cross between 'Honeycrisp' and 'Enterprise'), marketed as Cosmic Crisp®. ***A)*** *'WA 38' apples ready for harvest on the mother tree, located at the WSU and USDA-ARS Columbia View Research Orchard near Orondo, WA, USA. B) The 'WA 38' mother tree. C & D) Green spot, a corking disorder which results in green blemishes on the fruit peel and brown, corky cortex tissue. Symptom severity generally increases during fruit maturation and time in storage, resulting in cullage. E) Natural peel greasiness as a result of more advanced maturity at harvest can interfere with artificial waxes applied in the packinghouse after removal from postharvest storage, creating unappealing, dull spots. F) Green Spot symptoms can begin to appear while fruit is still developing on the tree. Photo Credits: A&B: Heidi Hargarten/ USDA-ARS; C&D: Bernardita Sallato/WSU; E: Carolina Torres/WSU; F: Ross Courtney/Good Fruit Grower.*

To develop full resolution reference genomes of superior quality, having skilled bioinformaticians is required. To train the next generation of bioinformaticians for agricultural genomic research, a national effort spearheaded by Auburn University, HudsonAlpha Institute for Biotechnology, and Washington State University was started in 2021 - The American Campus Tree Genomes project (ACTG). ACTG aims to break through institutional barriers that have traditionally prevented many students from accessing valuable, hands-on research projects and experience

in bioinformatics[7]. To accomplish this goal, a course has been developed to involve students in genome projects from inception, through analysis, to publication[8]. During the course, students learn genome assembly and annotation workflows using the raw sequence data from genomes of beloved trees (e.g., Toomer's oak and ‘d’Anjou’ pear at Auburn University, Sabal palm at University of South Carolina) and are listed as authors on the final publication. The ‘WA 38’ genome introduced here was developed through ACTG by students from Washington State University, presenting three major outcomes: 1) a fully annotated, chromosomal level, haplotype-phased genome of ‘WA 38’ utilizing PacBio HiFi, Dovetail Omni-C, and Illumina DNA and RNA sequencing data, 2) identification of unique regions of interest using a comparative genomics approach from the other economically important *M. domestica* cultivars including ‘Gala’ and ’Honeycrisp’, and 3) establishment of a containerized, reproducible, flexible, high performance computing workflow for complete genome assembly and annotation (Figure 2, Supplemental Figure 1).

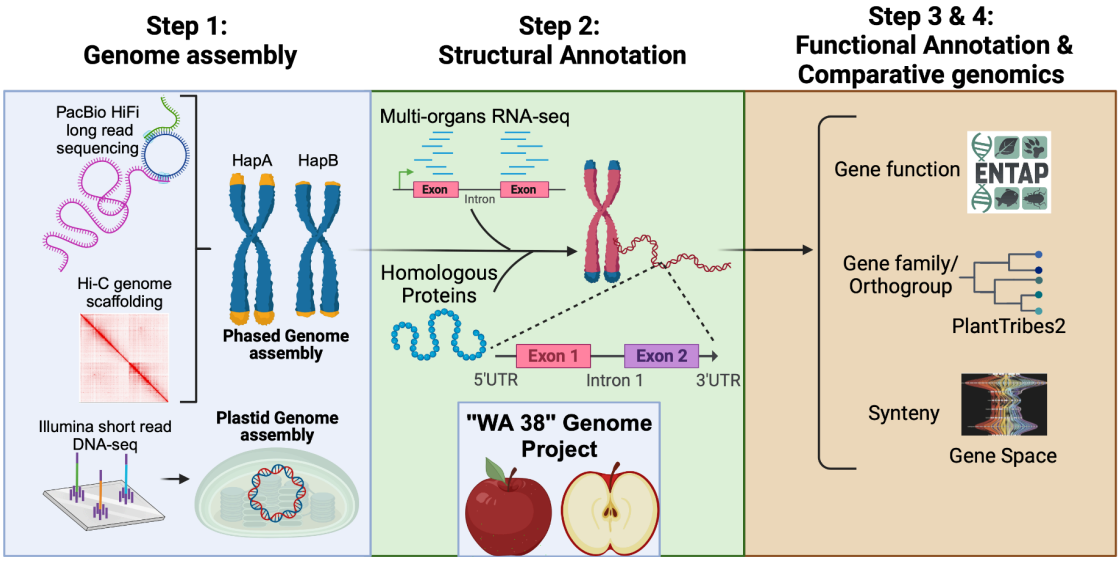

Figure. 2 Schematic chart of “WA 38” genome project.

7 https://hudsonalpha.shorthandstories.com/learning-from-the-trees/&sa=D&source=docs&ust=1704831742820941&usg=AOvVaw1rRBKfG02GkZH8ciIAxNwn

8 https://actg-wgaa.readthedocs.io/en/latest/index.html

Results

A complete, reproducible, publicly-available workflow

To ensure transparency and reproducibility, the 'WA 38' Whole Genome Assembly and Annotation (WA 38 WGAA) project workflow was made publicly accessible through a public GitHub repository[9]. This workflow includes detailed method documentation that scripts executed for each analysis with parameter settings, as well as any command line manipulation of the files generated. To enhance ease of use and reproducibility across diverse computational systems, each software utilized in the project has been containerized and shared on Docker Hub[10]. Any user that follows the workflow can successfully complete the analysis and reproduce the results. Furthermore, this workflow is designed to provide training that is applicable for a wide range of species. In fact, we are currently adapting this versatile methodology into a generic, species-agnostic workflow that will serve the broader American Campus Tree Genome (ACTG) community. As part of our commitment to knowledge sharing, we have initiated an ACTG course GitHub repository[11], leveraging resources from the WA 38 WGAA project. This repository comprises three main sub-repositories: 1) wgaa-compute: A generic whole genome assembly and annotation workflow template, derived from the WA 38 WGAA project, that can be adapted for other species; 2) wgaa-docker: The Docker recipes for all the software employed in the project; and 3) wgaa-doc: An interactive documentation repository containing teaching materials for current and future ACTG instructors, providing a collaborative space for instructors to learn from and contribute to the enhancement of the course materials.

Genome assembly

Sequence Quality Assessment

To begin, raw sequencing data (Table 1) was assessed for quality of reads. The Illumina shotgun short read data had sequencing adapters trimmed and the remaining sequence consisted of 807.2 million total reads with a mean length of 151bp for a total of 121.9 Gigabytes (GB) of data. Filtered Illumina data GC content is 38.3% and has 91.8% Q20 bases and 83.4% Q30 bases. Duplication rates ranged from 23.3% to 27.8%. PacBio long read raw data

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[9] https://gitlab.com/ficklinlab-public/wa-38-genome
[10] Docker images can be accessed at https://hub.docker.com/u/systemsgenetics
[11] https://github.com/actg-course/

consisted of 3.9 million reads from 499-49,283bp in length for a total of 60 GB. PacBio average read length was 15,305 to 15,685 bp. Sequence duplication rates ranged from 2.2% to 2.4%. PacBio sequence GC content is 38%. These metrics indicate high quality sequences from both short and long read technologies.

	Long Read		Illumina Short Read			
	PacBio HIFI		Shotgun DNA seq		OmniC-Seq	
	File1	File2	Read1	Read2	Read1	Read2
Total read	2,003,302	1,866,961	403,610,448	403,610,448	865,134,180	865,134,180
Number of bases (Gb)	31.4	28.6	121.89	121.89	130.6	130.6
Avergae length (bp)	15,685	15,305	151	151	151	151

Table 1. Yield of Illumina DNA short reads (Shotgun and Omni-C) and PacBio HiFi sequencing reads from young leaf tissues of 'WA 38'.

Genome complexity

Using a *k*-mer frequency approach, genome characteristics such as heterozygosity and genome size were estimated (Figure 3). Analysis of both short and long reads resulted in an estimated heterozygosity of ~1.35%, similar to estimates from the 'Honeycrisp' cultivar (1.27% (Khan et al. 2022)). Estimate genome size ranged from 466.5Mb from the short reads and 606Mb from the long reads. These estimates are lower than expected from other apple genomes ('Honeycrisp': 660-674Mb, (Khan et al. 2022) and 'Golden Delicious': ~701Mb, (Xuewei Li et al. 2016)). Additionally, the percent of unique sequence was estimated at 69.5% for the short reads and 53.4% for the long reads, with the long read estimate being more consistent with what is expected from the 'Honeycrisp' (51.7%) (Khan et al. 2022) and of wild apple species *Malus baccata* (58.6%) (X. Chen et al. 2019).

Genome assembly and scaffolding

Two phased haplomes, hereafter named HapA and HapB, were assembled and scaffolded using both PacBio long reads and Omni-C short reads. HapA is 677 Mbp in length, comprising 699 scaffolds with an N50 of 36.1 Mbp. HapB is 667 Mbp in length, comprising 229 scaffolds with an N50 of 37.2 Mbp. Additional assembly statistics for both haplomes are included in Figure 4. 'WA 38' has a comparable genome size to other previously sequenced apple cultivars, including its parent 'Honeycrisp' (Khan et al. 2022). Notably, the 'WA 38' scaffold N50 is the longest among all published apple genomes, indicating high levels of assembly contiguity.

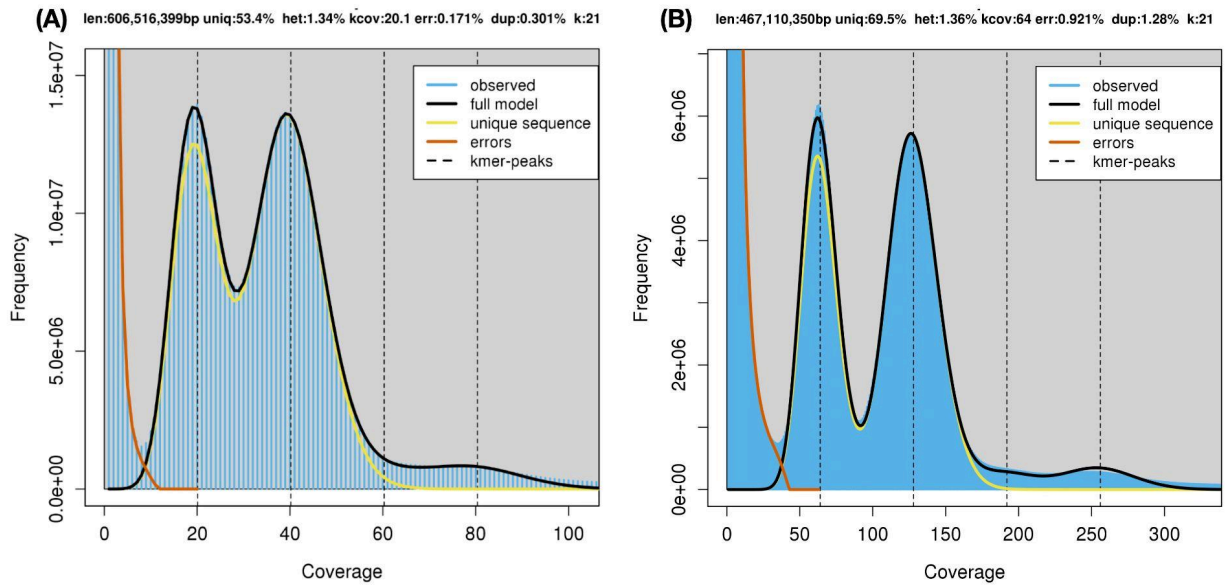
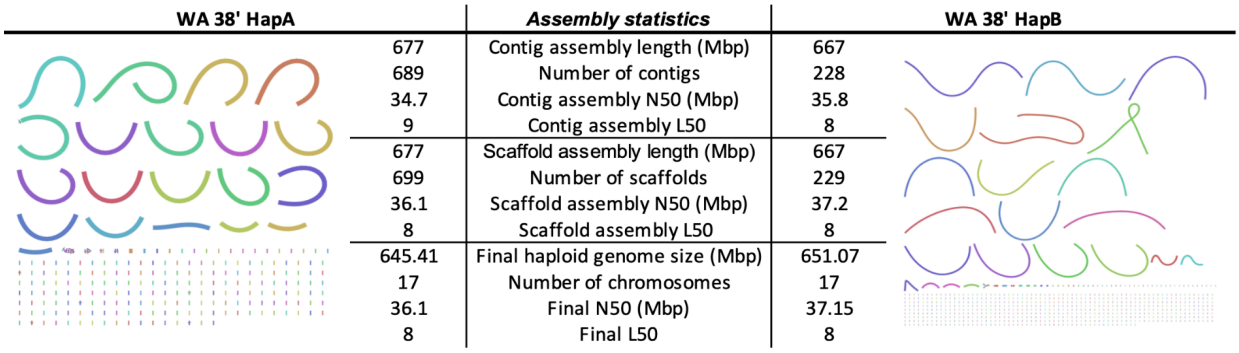


Figure.3 Genome complexity of 'WA 38' genome using PacBio long read data (A) and Illumina short read (B). The output figure was generated by GenomeScope (k=21).



WA 38' HapA	*Assembly statistics*	WA 38' HapB
677	Contig assembly length (Mbp)	667
689	Number of contigs	228
34.7	Contig assembly N50 (Mbp)	35.8
9	Contig assembly L50	8
677	Scaffold assembly length (Mbp)	667
699	Number of scaffolds	229
36.1	Scaffold assembly N50 (Mbp)	37.2
8	Scaffold assembly L50	8
645.41	Final haploid genome size (Mbp)	651.07
17	Number of chromosomes	17
36.1	Final N50 (Mbp)	37.15
8	Final L50	8

Figure 4 . Assembly statistics and Bandage plots of haplotype-phased assembly of 'WA 38'

Assembly Curation and Assessment

Hi-C maps of the haplome assemblies show no mis-assemblies (Supplemental Figure S2). For HapA and HapB, a total of 22 joins and 20 joins, respectively, were made in the scaffolding step to build the final assemblies into 17 chromosomes each, with the remaining scaffolds representing unincorporated contigs. Unincorporated contigs were investigated and found to be bacterial or other contamination and were removed. Based on the BUSCO analysis, both the HapA and HapB assemblies were ~98.7% complete, with only 19 BUSCOs missing and 12 partially detected. This level of BUSCO completeness suggests high genome completeness for both haplomes, comparable to the 'Honeycrisp' apple genome assembly which is the most contiguous of all apple genomes to date (Table 2) (Khan et al. 2022). HapA and HapB are

structurally similar; a total of ~44Mb are affected by structural variants and are mainly contributed by indels and repeat expansion and contractions (Supplemental Table S1 and Supplemental Figure S3). Additionally, three large inversions are observed on chromosomes 1, 11, and 13 (Supplemental Figure S4).

	'WA 38' HapA	'WA 38' HapB	Honeycrisp' HapA	Honeycrisp' HapB	Antonovka' Hap1	Antonovka' Hap2	'Gala' (Haploid concensus)	HFTH1; 'Hanfu' (Triploid)	GDDH13; 'Golden Delicious' (Double haploid)	'Golden Delicious' (Diploid)
Number Scaffold	17	17	473	215	222	114	877	18**	1,081	18**
Haploid genome size (Mbp)	645.41	651.07	674	660	651	636	652.4	658.9	643.2	742
N50	36.1	37.15	31.6	32.8	35.4	36.3	23.9	6.99	5.5	16
L50	8	8	8	8	8	8	NA	NA	NA	9
Number of protein-coding gene	48,227	54,479	47,563	48,655	45,200	44,969	45,352	44,677	40,175	57,386
Complete BUSCO (%) Assembly	98.7	98.7	98.6	98.7	97.7	97.5	97.9	98.6	98	82
Complete BUSCO (%) Annotation	98	98.4	96.8	97.4	97.4	97.1	95.5	93.6	96.1	68
Number of orthogroups in 26Gv2	10,385	10,536	10,351	10,367	10,284	10,302	9,890	9974	10,117	8824
Reference	This paper		Khan et al. 2022		Švara et al., 2023		Sun et al. 2021	Zhang et. 2019	Daccord et al. 2017	Velasco et al. 2010

*Table 2. Comparison of genomic features and assembly statistics of current assembly of 'WA-38' genome and previously published genomes of apples. NA: Data not available. ** Scaffolds not anchored to the 17 main pseudochromosomes in HFTH1; 'Hanfu' (Triploid) and 'Golden Delicious' (Diploid) assemblies were merged into one scaffold, thus the count of 18.*

Structural annotation

Repeat annotation

'WA 38' HapA contains 60.93% repeat regions and HapB 61.3% repeat regions, comparable to the percent of repetitive elements calculated for the 'Honeycrisp' genome (Khan et al. 2022). In both haplomes, the most dominant type of repeat element is long terminal repeat (LTR), followed by Terminal Inverted Repeat (TIR) (Table 3, Supplemental Table S2), consistent with that in 'Honeycrisp'.

	Class	'WA 38' HapA (%)	'WA 38' HapB (%)	Honeycrisp HapA (%)	Honeycrisp HapB (%)	'd'Anjou' pear Hap1 (%)	'd'Anjou' pear Hap2 (%)
LTR	Copia	9.6	10.31	9.73	9.6	5.6	5.73
	Gypsy	17.05	17.34	20.29	17.8	12.32	12.88
	unknown	14.85	14.58	14.89	16.86	8.46	10
TIR	CACTA	2.01	2.11	2.21	1.95	1.4	1.4
	Mutator	3.78	3.97	4.16	4.25	3.47	3.41
	PIF Harbinger	2.31	2.58	2.43	2.6	1.81	1.81
	Tc1_Mariner	0.91	0.14	0.15	0.27	0.13	0.11
	hAT	2.15	2.35	2.3	2.31	0.58	0.84
	polinton	0	0	0	0.01	0	0
nonLTR	LINE_elemnet	0.18	0.15	0.18	0.17	0.14	0.14
	unknown	0.07	0.08	0.09	0.18	0.06	0.06
nonTIR	helitron	2.83	2.57	2.95	3.18	1.56	1.92
Repeat region		2.76	2.01	2.91	2.78	3.98	4.22
Low complexity		3.14	3.1	NA	NA	NA	NA
Total		60.93	61.3	62.43	61.97	39.78	42.52
Reference		This paper		Khan et al. 2022		Yocca et al., 2023	

Table 3. Summary of repetitive element annotation in the 'WA 38' and other apple genomes.

Gene space annotation

To annotate the gene space, we utilized a combination of *ab initio* prediction and evidence-based prediction with transcriptome and homologous protein, functions implemented in BRAKER2. However, BRAKER2 was unable to annotate UTR regions and yielded erroneous splice variants (Supplemental Figure S5). Therefore, the gene models were further processed with PASA (Haas et al. 2003) and a custom script. A total of 48,227 and 54,479 genes were annotated from HapA and HapB, respectively, more than most published apple genomes (Table 2, Supplemental Table S3). The complete BUSCO scores for HapA and HapB annotations are 98.0% and 98.4%, respectively. 'WA 38' HapB has the highest BUSCO score among all *M. domestica* genomes sequenced to date (Table 2). The average protein annotated from HapA and HapB contains 376.13 and 355.10 amino acids, respectively, very similar to protein lengths from other *M. domestica* annotations (Supplemental Table S4). On average, ~1.3 splice variants were identified for each gene in both HapA and HapB annotations. The only other apple genome with splice variant annotation is 'Honeycrisp', and on average, 1.05 splice variants were annotated per gene (Supplemental Table S4). Additionally, 57.2% and 52.1% of the annotated transcripts from HapA and HapB, respectively, contain untranslated regions (UTRs). Notably,

‘WA 38’ is the only other apple genome besides the ‘GDDH13’ genome that has more than half of the genes annotated with UTRs.

The ‘WA 38’ genes were named in accordance with the convention used by the ‘Honeycrisp’ annotation. The convention is as follows - *Maldo.cc.v1a1.ch10A.g00001.t1*, where cc stands for the commercially trademarked brand name ‘Cosmic Crisp ®’. This convention meets recommendations proposed by the AgBioData consortium to reduce gene ID ambiguity and improve reproducibility.

Functional Annotation

EnTAP (Hart et al. 2020) functional annotation assigned functional terms to 91.2% and 88.9% of proteins annotated from HapA and HapB, respectively. Specifically, an average of 85% of all proteins (including both HapA and HapB) have strongly supported hits in the NCBI RefSeq (O’Leary et al. 2016) database, 74% were annotated with an InterPro term, and 86% have functional annotations from at least one of the databases included in InterProScan. Additionally, EggNOG (O’Leary et al. 2016; Huerta-Cepas et al. 2019) search provided extra function information: 88% of the annotated proteins were assigned into EggNOG orthogroups, 82% were annotated with protein domains, 21% were classified into KEGG pathways, and 62%, 53%, and 59% proteins were annotated with GO biological process, cellular component, and molecular function terms, respectively (Supplemental Table S5).

Comparative Analyses

Synteny and gene family analyses were performed to investigate the similarity and uniqueness of ‘WA 38’ genome to other closely related species and cultivars.

Synteny analysis was performed with genomes of ‘WA 38’, one of its parents, ‘Honeycrisp’, and the most commonly referenced apple genome, ‘GDDH13’, using GeneSpace (Figure 5).

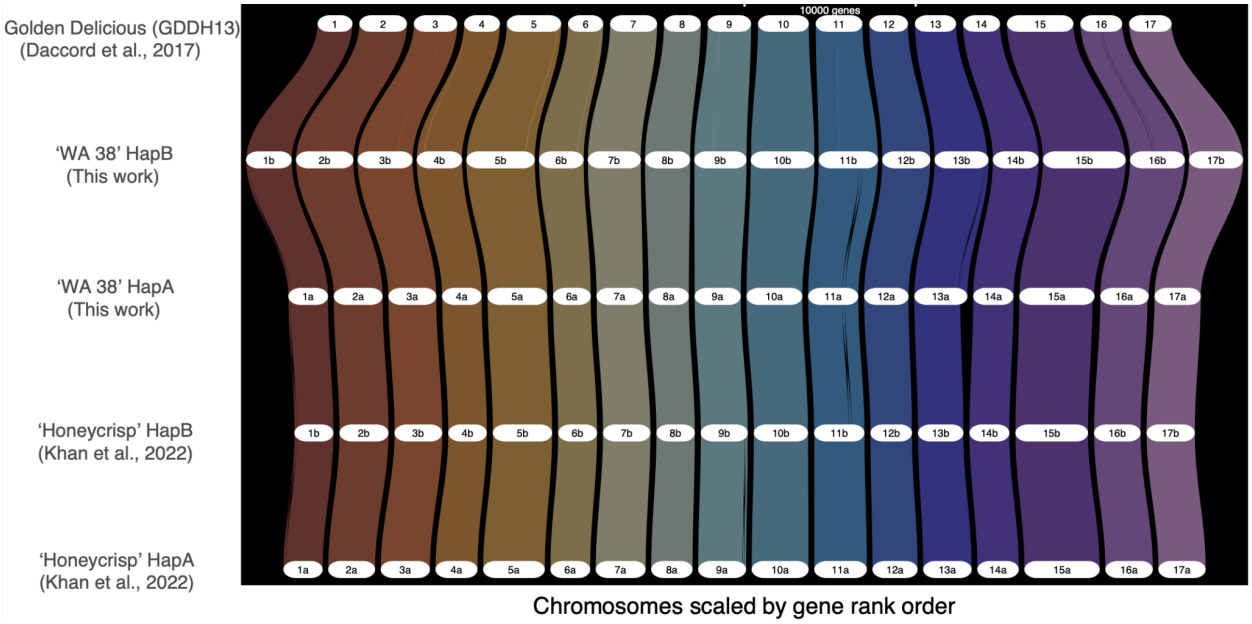


Figure 5. Riparian plot comparing 'WA 38' Haplotype A and B with 'Honeycrisp' Haplotype A and B and Golden Delicious (GDDH13) genomes.

Gene family analysis is performed using PlantTribes2 and the pre-constructed 26Gv2-scaffold orthogroup database (Wafula et al. 2022). Out of the 18,110 pre-constructed orthogroups, proteins from all apple annotations [5 published genomes ('Honeycrisp' (Khan et al. 2022), 'Gala' (Sun et al. 2020), 'Hanfu' (L. Zhang et al. 2019), 'Antonovka' (Švara et al. 2023), and the GDDH13 'Golden Delicious' (Daccord et al. 2017) genomes) and the 'WA 38' genome from this work] are found in 11,671 orthogroups. 'Golden Delicious' Genome v1.0 (Velasco et al. 2010) was omitted from this analysis due to poor annotation quality. Proteins from HapA and HapB of 'WA 38' were classified into 10,385 and 10,536 orthogroups, respectively, similar or slightly higher in number compared to previously published *M. domestica* genomes, including 'Honeycrisp', 'Gala', and 'GDDH13' (Table 2, Figure 6). An investigation into shared and unique orthogroups showed that most orthogroups (8,807 or 75%) are shared by all six apple genomes considered. Additionally, 875 orthogroups are shared by both 'WA 38' haplomes and the seven other annotations (the two haplomes from 'Honeycrisp' and 'Antonovka 172670-B' are counted as two annotations). Annotations that shared the largest number of orthogroups with 'WA 38' is 'Honeycrisp', as expected due to being one parent of 'WA 38' (Supplemental Table S6). These results indicate that the 'WA 38' annotations capture genes in virtually all *M. domestica* orthogroups. Additionally, 41 orthogroups were unique to 'WA 38' (i.e. present only in the two

‘WA 38’ haplomes) and 39 and 55 orthogroups were unique to each haplome of ‘WA 38’ (Figure 6).

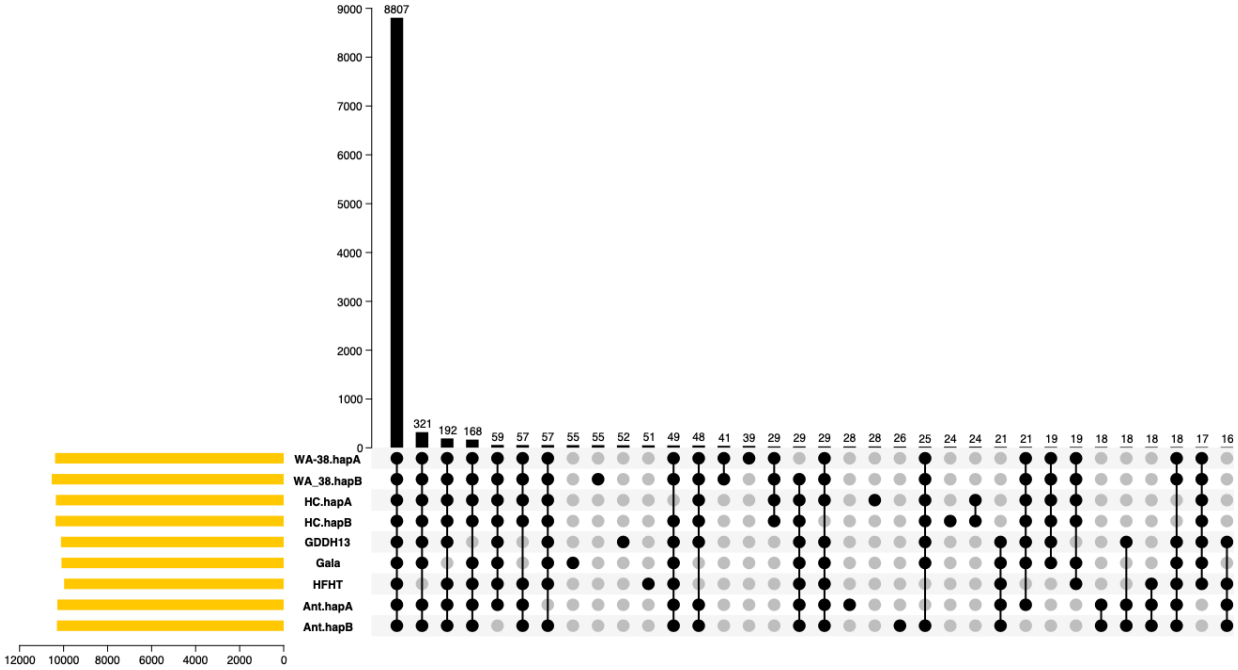


Figure. 6 Upset plot of shared and unique orthogroups among Malus domestica genomes.

In addition to identifying the shared and unique orthogroup, a CoRe OrthoGroup (CROG) - Rosaceae analysis is performed to further investigate orthogroup contents. As expected, in the CROG gene count clustermap (Supplemental Figure S6), ‘WA 38’ clustered closely with ‘Honeycrisp’. The ‘WA 38’ + ‘Honeycrisp’ group is clustered with other apple genomes, including a recently published ‘Antonovka’ genome (Švara et al. 2023) and the ‘Gala’ genome (Sun et al. 2020), indicating similar gene counts in a vast majority of orthogroups among *M. domestica* cultivars. The CROG gene count *z*-score box plot shows (Supplemental Figure S7) that the average *z*-score of ‘WA 38’ gene counts are slightly higher than expected (with 0 as the perfect score), indicating that there are a number of CROGs containing more genes from the ‘WA 38’ annotations compared to other apples.

Plastid Genomes Assembly and Annotation

The chloroplast genome of the ‘WA 38’ apple is 159,915 bp in length, which is smaller than most assembled *M. sierversii* chloroplast genomes (Xueli Li et al. 2022; Miao et al. 2022; Naizaier et al. 2019; Yan et al. 2019; Zhao et al. 2019; Ha et al. 2020). The plastome consisted of a typical

quadripartite structure with a pair of inverted repeat regions (IR) of the same length (26,352 bp) separated by a large -single copy region (LSC) (88,052 bp) and a small -single copy region (SSC) (19,159 bp). The inverted repeat regions and the SSC regions were all similar in length to that of other *M. sierversii* cultivars (Xueli Li et al. 2022; Miao et al. 2022; Naizaier et al. 2019; Yan et al. 2019; Zhao et al. 2019; Ha et al. 2020). A total of 134 unique genes were annotated, including 86 protein-coding genes, 42 tRNA genes, and 7 rRNA genes. Moreover, eight protein-coding genes (*ycf1, ycf2, rpl2, rpl23, ndhB, rps7, rps12, rps19-fragment*), ten tRNA genes (*trnE-UUC, trnI-GAU, trnA-UGC, trnL-CAA, trnM-CAU, trnN-GUU, trnR-ACG, trnI-CAU, trnN-GUU, trnV-GAC*), all four rRNA genes (*rrn16, rrn23, rrn4.5, rrn5*) were located wholly within the IR regions (Figure 7). Twelve protein-coding genes, eight tRNA genes, and one rRNA gene (*rrn16*) contain introns. The majority of which contained one intron (19 genes), with only two genes (*pafl* and *clpP1*) containing two introns.

The mitochondrial genome of the ‘WA 38’ apple is 451,423bp long and contains 64 annotated genes. This annotation includes 4 rRNA genes (two copies of 26S, and one copy of both 18S and 5S), 20 tRNA genes (including two copies of *trnaA-FME* and three copies of *trnaF-GAA*), and 40 protein-coding genes (including two copies of *atp1, apt8, cox3, nad6, nad7, rnaseH, rps12*, *rps3*, and *sdh4*). (Figure 8)

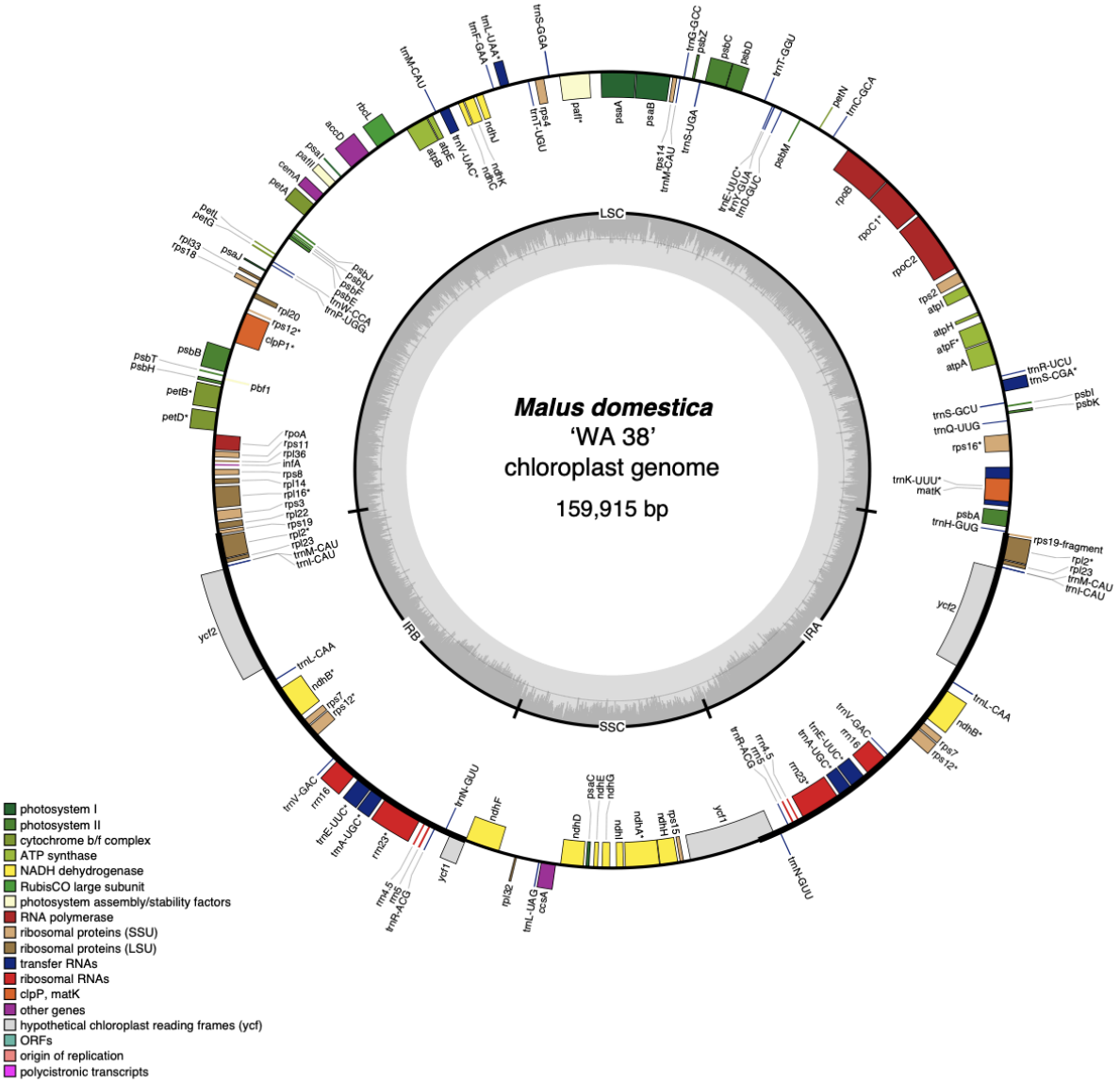


Figure.7 Chloroplast genome map of 'WA 38' with annotation.

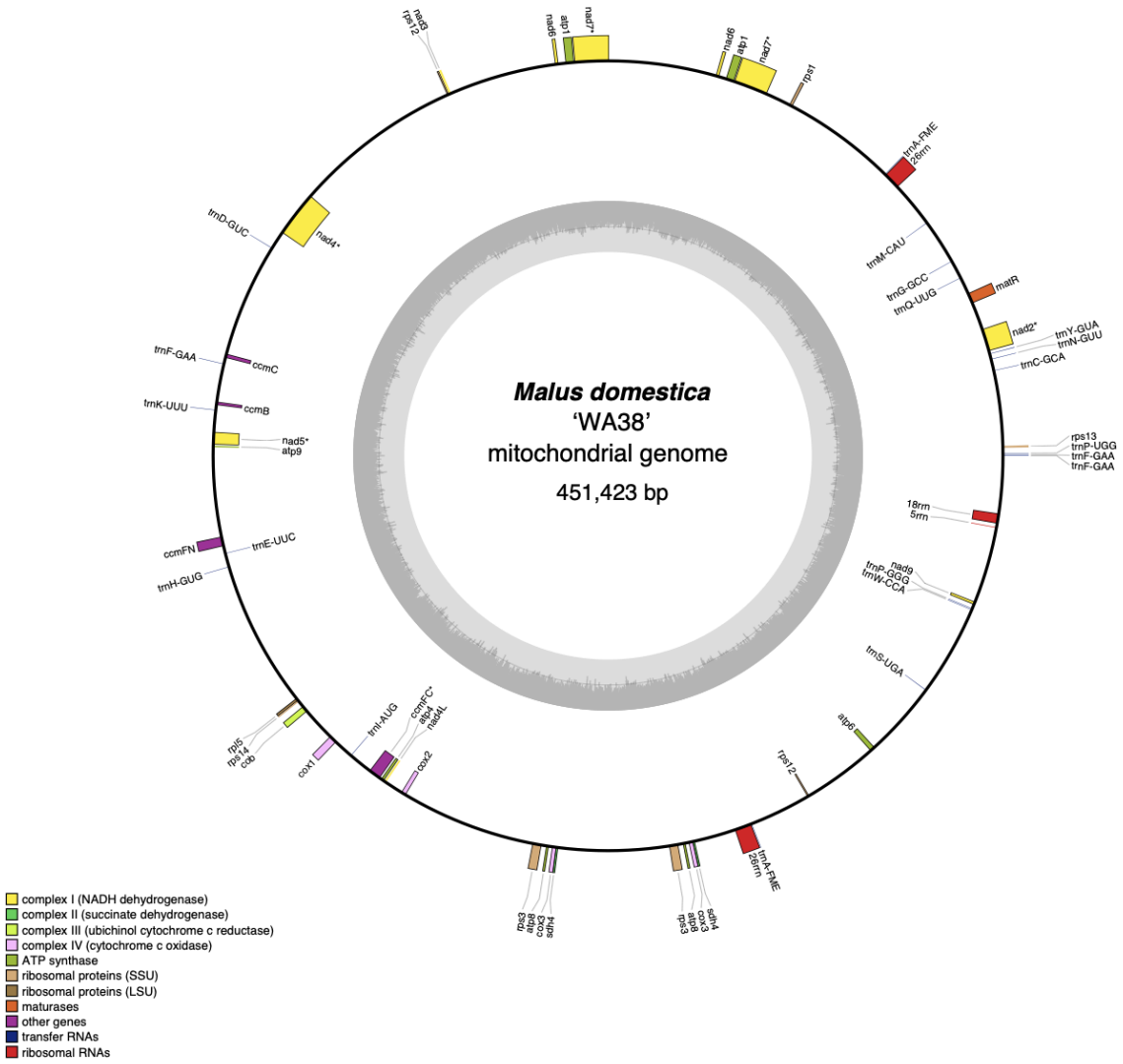


Figure. 8 Mitochondrial genome map of 'WA 38' with annotation.

Methods

Workflows developed for each stage of the project and the summary workflow of the whole project are available in Supplemental Figure S1. Scripts with parameters for each computation step and methods in markdown format are available in GitHub at: https://gitlab.com/ficklinlab-public/wa-38-genome. Please refer to the GitHub material for step-by-step description of the workflow.

Sample Collection

Approximately 20 grams of young leaf material was harvested from the *Malus domestica* 'WA 38' mother tree at the Washington State University and USDA-ARS Columbia View Research Orchard near Orondo, WA, USA and flash-frozen in liquid nitrogen. Tissue was sent to the HudsonAlpha Institute for Biotechnology in Huntsville, AL, USA for DNA extraction, sequencing library preparation, and sequencing, following the same protocol (detailed below) used to generate the 'd'Anjou' pear genome (Yocca et al. 2023).

To assess heterozygosity and genome size of 'WA 38', DNA was isolated using a standard CTAB isolation (Doyle and Doyle 1987). Illumina TruSeq DNA PCR-free libraries were constructed from 3 ug of input DNA following the manufacturer's instruction, and sequenced on an Illumina NovaSeq6000.

For PacBio HiFi sequencing, high molecular weight DNA was isolated using a Nanobind Plant Nuclei Big DNA kit (Circulomics), with 4 g of input tissue and a 2-hour lysis. DNA purity, quantity, and fragment sizes were measured via spectrophotometry, Qubit™ dsDNA Broad Range assay (Invitrogen™), and Femto Pulse system (Agilent), respectively. DNA that passed quality control was sheared with a Megaruptor (Diagenode) and size-selected to roughly 25 kb on a BluePippin. The SMRTbell Express Template Prep Kit 2.0 (PacBio) was used to construct the PacBio sequencing library, and HiFi reads were produced using circular consensus sequencing (CCS) mode with two 8M flow cells on a PacBio Sequel II long-read system.
To scaffold PacBio HiFi contigs into chromosome pseudomolecules, a Dovetail Genomics Omni-C library was generated using 1 g of flash-frozen young leaf material as input following the manufacturer's instruction (Dovetail Genomics), and sequenced on an Illumina NovaSeq6000 S4 PE150 flow cell.

Sequence quality assessment and genome complexity analysis

Adapter sequences were trimmed from the raw Illumina shot-gun DNA reads using fastp (v0.23.2) (S. Chen et al. 2018) with all the other trimming functions disabled. Both the raw and trimmed Illumina reads, PacBio HiFi reads, and Omni-C Illumina reads were assessed for quality with FastQC (v0.11.9) (Andrews, 2010). Genome complexity, *i.e.* nuclear genome size and ploidy, was estimated using Jellyfish (v2.2.10) (Marçais and Kingsford 2011). With trimmed paired-end Illumina reads as input and a k-mer size set to 21, a k-mer count file was generated by Jellyfish. The k-mer histogram, also created by Jellyfish, was visualized in GenomeScope

(v1.0) (Vurture et al. 2017) with the following parameters: k-mer size = 21, Read length = 151, and Max k-mer coverage = 1000. A summary statistic report of the sequence quality and complexity analysis was generated with MultiQC (v1.13a).

Genome Assembly

Genome assembly and scaffolding

Phased haplomes were assembled by Hifiasm (v0.16.1) (Cheng et al. 2021) with default parameters, using both the Omni-C data and the PacBio HiFi long reads. The statistical summary of the assembly was produced using the assimilation_stats Perl scripts described in (Earl et al. 2011). Both hifiasm-assembled haplotype unitigs were then sorted by MUMmer (v3.23) (Kurtz et al. 2004) using the 'nucmer' function with flag -maxmatch. The resulting files were uploaded to the Assemblytics web server[12] (Nattestad and Schatz 2016) to visualize structural variations in two haplotype unitigs with the default settings.
Following the initial assembly step, bwa (H. Li and Durbin 2009) was used to index the draft contigs, and subsequently to align the Hi-C reads to the indexed contigs. The sorted files were input into Phase Genomics hic_qc[13] to validate the overall quality of the library. Both assembled haplomes were scaffolded into chromosomes with YaHS (Danecek et al. 2021; Zhou, McCarthy, and Durbin 2022), using default parameters.

Assembly curation and completeness assessment

Hi-C files were generated using YaHS Juicer Pre (v1.2a.2-0) with flag -a allowing manual curation. The resulting files were used as input for Juicer Tools Pre (v 1.22.01) to generate Hi-C contact maps (Zhou, McCarthy, and Durbin 2022; Durand et al. 2016). Juicebox Assembly Tools (v1.11.08) was used to explore the Hi-C maps for miss-assemblies (Robinson et al. 2018) . After manual examination of the Hi-C maps, the final genome assembly was generated by linking remaining files from YaHS Juicer Pre and original HiFi scaffold, using YaHS Juicer Post (v 1.2a.2-0, (Durand et al. 2016)).

For consistency and reproducibility, 'WA 38' chromosomes were renamed and reorientated to match published genomes. First, MUMmer (v3.23) was used to align the 'WA 38' assembly to the 'Gala' v1 HapA assembly using the –maxmatch parameter for unique matches (Kurtz et al.

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[12] http://assemblytics.com,
[13] Available at https://github.com/phasegenomics/hic_qc

2004; Sun et al. 2020). Next, Assemblytics dotplot was used to identify 'WA 38' scaffolds that aligned with the 'Gala' v1 chromosomes and 'WA 38' scaffolds were renamed accordingly. To determine orientation, each 'WA 38' chromosome was aligned to the corresponding 'Gala' v1 chromosomes using LASTZ (v 1.02.00) implemented in Geneious (v9.0.5, Harris . 2007) with the 'search both strands' option. The chromosomes on the reverse stand were reoriented with the Reverse Complement (RC) function in Geneious (Supplemental Figure 8). The resulting assembly was searched against NCBI's RefSeq Plastid database[14] using megablast and a custom virus and bacteria database using kraken (v2.1.3) to identify contaminants. Scaffolds identified as plastid or microbe contaminants were removed in the final assembly. The two final haplome assemblies were compared to each other using MUMmer and Assemblytics as described above to identify structural variants. Benchmarking universal single-copy gene orthologs (BUSCO, v5.4.3_cv1) analysis was performed in genome mode with the eudictos_odb10 database to assess the completeness of gene content (Manni et al. 2021).

Structural and functional annotation

Repeat annotation

Repetitive elements from both haplotypes were annotated using EDTA (v2.0.0, (Ou et al. 2019)), with flags 'sensitive=1' and 'anno=1'. The full coding sequence from 'Gala' HapA, obtained from the Genome Database for Rosaceae (GDR, (Jung et al. 2019)), was used as reference to aid repeat finding. The custom transposable element library generated by EDTA was then imported to RepeatMasker (Smit et al. 2015) to further identify potentially overlooked repetitive elements. Repeatmasker was used to generate masked versions of the genome, where repetitive elements are converted to N to preserve the spacing but will not be included in the downstream annotation.

Gene Annotation

To annotate gene space, a combination of *ab initio* prediction and evidence-based prediction were performed with two rounds of BRAKER using transcriptome and homologous protein evidence. PASA (v2.5.2) (Haas et al. 2003) was then used to refine gene models and add UTR annotation. Lastly, a custom script was used for filtering. The detailed methods are described below.

[14] https://www.ncbi.nlm.nih.gov/genome/organelle/

BRAKER1 - annotation with transcriptome evidence

To perform transcriptome guided annotation, same data RNA-seq data from Khan et al. (2022) (eight tissue types from six pome fruit cultivars including 'WA 38') were first aligned to the assembled 'WA 38' masked haplomes using the STAR aligner implemented in GEMmaker (v2.1.0) (Hadish et al. 2022) Nextflow workflow. The resulting read alignments were used as extrinsic evidence in BRAKER1 (Hoff et al. 2016) to predict gene models in each soft-masked haplome with the following parameters: --softmasking, --UTR=off, --species=malus_domestica.

BRAKER2 - annotation with homologous protein evidence

To provide protein evidence data for BRAKER2 (Brůna et al. 2021), protein sequences from three sources were used: 1) Predicted protein sequences of 13 Rosaceae genomes retrieved from GDR (*Fragaria vesca* v4a2(Y. Li et al. 2019), *Malus baccata* v1.0(X. Chen et al. 2019), *M. domestica* var.Gala v1(Sun et al. 2020), *M. domestica* var.GDDH13 v1.1 (Daccord et al. 2017), *M. domestica* var. Honeycrisp v1.0(Khan et al. 2022), *M. sieversii* v1(Sun et al. 2020), *M. sylvestris* v1(Sun et al. 2020), *Prunus persica* v2.0.a1(Verde et al. 2017), *Pyrus betulifolia v1.0(Dong et al. 2020)*, *P. communis* var.d'Anjou v1(Yocca et al. 2023), *P. pyrifolia* var. Nijisseikiv v1.0(Shirasawa, Itai, and Isobe 2021)*, Rosa chinensis* var.Old Blush v2.0.a1(Raymond et al. 2018), and *Rubus occidentalis* v3 (VanBuren et al. 2018)); 2) Peptide sequences predicted from *de novo* transcriptome assemblies from the 'Honeycrisp' genome annotation(Khan et al. 2022); and 3) Viridiplantae OrthoDBv11 (Kuznetsov et al. 2022). In the same manner as BRAKER1, the masked haplome assemblies were used as input.

TSEBRA - transcript selection

The gene annotation results from BRAKER1 and BRAKER2 were merged and filtered based on the supporting evidence using TSEBRA (v.1.0.3) (Gabriel et al. 2021) with the default configuration (file obtained in August 2022) provided by TSEBRA developers.

PASA - gene model curation and UTR annotation

Two sources of transcriptome assembly evidence were obtained to facilitate PASA annotation: 1) Transcript sequences predicted from *de novo* transcriptome assemblies used by 'Honeycrisp' genome annotation; and 2) Reference guided assemblies were created with read alignment files from GEMmaker (see the BRAKER1 section for details) using Trinity with max intron size set to 10,000. Four rounds of PASA (v2.5.2) curation were performed using the aforementioned evidence and a starting annotation. The first round of PASA curation used TSEBRA annotation

as the starting annotation, and annotations from the previous round were used as the starting annotation for rounds two through four. The curation results from each round were manually inspected using the PASA web portal. No significant improvement was observed after the fourth round of curation, therefore no further rounds were performed.

Gene model filtering and gene renaming

Repeat and gene model annotations were loaded to IGV (v2.15.1, (Robinson et al. 2011)) for manual inspection. Three types of erroneous gene models were observed consistently throughout the annotations. Type 1: Genes overlapping with repeat regions (e.g. transposon was wrongly annotated as a gene), Type 2: Gene models overlapping with each other on the same strand (e.g. single gene was wrongly annotated with multiple gene models), and Type 3: Gene models with splice variants that had no overlap (e.g. different genes were wrongly annotated as the single gene's splice variants). A custom script was used to address these errors. The Type 1 error was resolved by removing genes with 90% of its coding region overlapped with repeat regions. The Type 2 error was resolved by removing the shorter gene of a pair that overlaps on the same strand. The Type 3 error was resolved by splitting splice variant models with no overlap into two separate gene models. Finally, custom scripts were used to generate the final annotation files (gene, mRNA, cds, protein, gff3) and rename genes to match the naming convention used for 'Honeycrisp'(Khan et al. 2022).

Functional Annotation

The final gene sets from both 'WA 38' haplomes were annotated with EnTAPnf (Hart et al. 2020) with Interproscan, Panther, RefSeq, and uniprot_sprot databases that are automatically downloaded using the download.py script provided by EnTAPnf.

Comparative Analysis

Synteny analysis

A synteny comparison was performed using GENESPACE (Lovell et al. 2022) with five *Malus domestica* assemblies and annotations, (GDDH13(Daccord et al. 2017), both haplomes from 'Honeycrisp'(Khan et al. 2022), and both haplomes from 'WA 38').

Gene family analysis

Gene family or orthogroup analyses were carried out to identify shared and unique gene families in 'WA 38' and other pome fruit genomes (i.e., *Malus* sp. and *Pyrus* sp. A full list of genomes analyzed can be found in Supplemental Table S7) following the method described by (Khan et al. 2022). Briefly, predicted protein sequences from the selected pome fruit genomes were classified into a pre-computed orthogroup database (26Gv2.0) using the both HMMscan and BLASTp option implemented in the GeneFamilyClassifier tool from PlantTribes2 (Wafula et al. 2022). Overlapping orthogroups among *M. domestica* genomes were calculated and visualized with the UpSet plot function implemented in TBtools v2.030 (Chen C., 2023).

A Core OrthoGroup (CROG) - Rosaceae gene count analysis was carried out following the method described by Wafula et al. 2022. First, a CROG gene count matrix was created by counting genes classified into CORGs from each pome fruit genome. Next, the matrix was visualized as a clustermap using the Seaborn clustermap package (CROGs with standard deviation of 0 were removed prior to plotting) with rows normalized by *z*-score. Finally, the derived *z*-score of CROGs in each genome was summarized into a boxplot to illustrate z-score distribution using the boxplot function in Seaborn.

Chloroplast & Mitochondria Assembly and Annotation

The chloroplast genome was assembled from trimmed Illumina shot-gun DNA reads using NOVOplasty (v4.3.1, (Dierckxsens, Mardulyn, and Smits 2017)) with the *Malus sierversii* chloroplast genome (NCBI accesion ID: MH890570.1, (Naizaier et al. 2019)) as the reference sequence and the NOVOplasty *Zea mays RUBP* gene as the seed sequence. The assembled chloroplast was annotated using GeSeq[15] (website accessed on Dec. 19th, 2023) (Tillich et al. 2017) with default settings for 'circular plastid genomes for land plants' and the following parameters: annotating plastid inverted repeats and plastid trans-spliced *rps12*. Additionally, annotations from third party softwares Chloë (v0.1.0) and ARAGORN (v1.2.38), as well as a BLAT (v.35×1) search against all land plant chloroplast reference sequences (CDS and rRNA), were integrated with the GeSeq results(Tillich et al. 2017). Genes identified by multiple tools were manually reviewed to produce the final, curated annotation. The curated chloroplast annotation was visualized by OGDRAW (v1.3.1) (Greiner, Lehwark, and Bock 2019).

[15] https://chlorobox.mpimp-golm.mpg.de/geseq.html

The mitochondrial genome sequence was isolated from the Hifiasm assembled contigs using MitoHifi (v3.2) (Uliano-Silva et al. 2023). The *Malus domestica* mitochondria sequencing from NCBI (NC_018554.1, (Goremykin et al. 2012)), which contained 57 genes consisting of 4 rRNAs, 10 tRNAS, and 33 protein-coding genes, was used as the closely related reference sequence. Briefly, MitoHifi compares the assembled contigs to the reference mitogenome using the BLAST algorithm. The resulting contigs were manually filtered by size and redundancy and then are circulated. To increase the annotation quality, GeSeq was deployed in mitochondrial mode with the *M. domestica* NCBI rRefsSeq sequence to annotate the 'WA 38' mitochondria assembly. Fragmented genes from the annotation were manually removed prior to visualization in OGDRAW (v1.3.1).

Availability of source code and requirements

Project name: 'WA 38' whole genome assembly and annotation
Project home page: https://gitlab.com/ficklinlab-public/wa-38-genome
Operating system(s): Platform independent
Programming language: bash, python, perl
Other requirements: singularity, nextflow, java, python
License: Not applicable
Any restrictions to use by non-academics: No restrictions
RRID: Not applicable

Data Availability

Data is available upon request. Please contact huiting.zhang@wsu.edu for data requests.

Competing interests

The author(s) declare that they have no competing interests.

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Authors' contributions

L.H and S.F acquired funding for this project. All authors contributed to data analysis, data interpretation, and manuscript writing.

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