# Results

## Characterization of shared and species-specific chromatin states

We generated an universal chromatin states (CS) map annotation from ten common epigenomic marks using hiHMM software for the three widely-studied model plant species: *Arabidopsis thaliana*, *Oryza sativa* and *Zea mays*. We focused our analysis on a model with 16 states (**supplemental fig. S1**; see **Methods**). The states were divided into 5 functional groups (bivalent, active, divergent, repressive and quiescent/no signal), with different levels of genome coverage, TE enrichment and overlap with other genomic features (**fig. 1**).

Co-occurrence of pairs of epigenetic marks exists between these species, but there are clearly specific patterns in both, CS and correlation analyses (**fig. 1**; **supplemental fig. S2**). Despite the diversity of the data, we found some conserved chromatin definitions such as Bivalent TSS/Promoter CS1, strongly linked to all active marks with very low enrichment in H3K27me3 and without clear presence of heavy repressive marks like 5mC and H3K9me2; and Active CS6, established in gene bodies and mainly constituted by H3K36me3, H3K4me2, H3K4me3 and H3K9ac in all the species. On the other hand, most of the states definitions strayed with some species-specific nuances at different levels, which could actually reflect our understanding of species-specific biology and how epigenomic complexity has evolved in plants. From less to more divergent: 1) States which shared genomic distribution and were constituted by marks with same roles, but covered with different marks like Heretochromatin 1 strong CS11 and Heterochromatin 2 weak CS12 (**fig. 1**). Repressive marks, also pinpointed in the correlation analysis with the highest inter-species variance (**supplemental fig. S2**), suggested two distinct types of heterochromatin across species requiring H3K27me3 for strong and H3K9me2 for weak definitions in *A. thaliana*,but not necessary in *O. sativa* and *Z. mays*. 2) Landscapes whose marks and genomic distribution gradually transitioned between species. A good case representing this could be Active weak TSS > TES CS8, mainly dominated by H3K36me3 deposition in gene bodies and TSS in *A. thaliana*,while in the two remaining species H3K4me2 is added and distribution changed towards the TES. 3) Ultimately, divergent region CS10 with a totally different mark and genomic distribution profile. CS10 corresponded to heterochromatic, bivalent and active states in *A. thaliana*, *O. sativa* and *Z. mays*, respectively.

We next performed additional annotation analyses based on non-common chromatin proteins and histone marks tracks to test our states definitions (**fig. 2, bottom panel**). There were evidence supporting our interpretation of the states for each species under study. For example: RNA polymerase II (Pol2) significantly located in all active and several bivalent states, and enrichment of the well-known H3K9-demethylase (IBM1) and transposon-methylase (CMT3) over heterochromatic states in *A. thaliana*. Essentially, all non-common active and repressive histone marks/variants evaluated were enriched in active/bivalent and heterochromatic states, respectively, with only two exceptions: H3K27me1 location in Bivalent Promoter CS2 in *A.thaliana*, which did not impact the state definition because this was already presented as bivalent due to the presence of H3K27me3; and H3K9me1/me3 in Active gradual bivalent flank > intergenic CS7 in *O. sativa*. Although the initial definition included gradual bivalent, this was only alluding to *Z. mays* as *O. sativa* CS7 was absent of any repressive mark, therefore, this would pontentially increase CS7 relation between both Poaceae-family members. We decided to stay conservative and keep our initial interpretation because H3K9me3 data is not available for all the species. It is worth mentioning that most of the transcription factors (TFs) observed in heterochromatin states were related with flowering, organ missed in our collection, and cell-cycle/division functions, previously described as present in chromatin barriers and strictly under control with low levels of expression (Feng & Michaels, 2015; Velay, Méteignier, & Laloi, 2022).

Taking advantage of the inter-species approach, we further evaluated if the states could involve evolutionary information. We observed a remarkable gradient across functional groups, excluding quiescent/no signal from the analysis due to the lack of epigenetic regulation (**fig. 3**; **supplemental fig. S3**). We found a decreasing trend in gene functional convergence (KO and GO), number of protein-coding genes and their corresponding proportion of orthologous relationships following active > bivalent > divergent > heterochromatin order (represented by CS6 > CS1 > CS10 > CS11, respectively). Additionally, most of the PhastCons elements genomic overlaps were located in active and bivalent states (**fig. 2**). Conserved non-coding elements (CNEs) co-localization in the same states for *A. thaliana* and the greater number of CNEs enriched states when comparing both species of monocots, again showed how CS could reflect the closer distance between *O. sativa* and *Z. mays*. Even though the majority of the states enriched in Conserved TF binding-sites (BS) were active and bivalent in *A. thaliana* and *O. sativa*, we did not appreciate a constrained pattern for all the species in TF motifs and genetic variability annotation modules (**fig. 2**). On the opposite side to conservation, these results could indicate that state information is still useful, because significant overlaps were detected, but it would probably reflect species-specific features in genetic variability and TF motifs contexts.

Taking together, these discoveries introduced a plant inter-species chromatin state single annotation as a resource to provide conservation and diversity evolutionary epigenomic information for future studies.

## Chromatin states features improve predictions of paralogs functional divergence

In order to exemplify an application of the resource generated and exploiting that our approach could differ between constituvely active and repressive states, we reproduced two previously published models predicting *A. thaliana* genetic redundancy (Cusack et al., 2021; Ezoe, Shirai, & Hanada, 2021) including CS information. As far as we know, *A. thaliana* was the only organism under study with an experimentally validated set of mutants for paralogous gene pairs which allowed the development of these models. Under the initial hypothesis that two paralogs covered by divergent state profiles are more likely to have different functions, we computed simmilarity and distance metrics between both CS profiles and fed these data to the abovementioned models (**fig. 4, top panel**; see **Methods**).

For the models developed by Ezoe et al.,2021 (**fig. 4a-d**), we first checked if the custom chromatin state metric (CCSM; see **Methods**) proposed could be a determinant of functional divergence using the same paralogous gene pairs as the original article (**fig. 4b**). High and low CCSM values were significantly associated to high and low diversified pairs, respectively (P-value = 3.4e-15, two tailed Wilcoxon rank sum test). In spite of the fact that epigenomic features tested in the reference did not pass this threshold (so the models were computed without including epigenetic information), our CS metric even joined the two best explanatory variables Ka/Ks and Re/Ks (see **Methods**) in terms of relative importance (**fig. 4a**). These results pointed the need to use integrative metrics when predicting genome elements and mechanisms. Logistic regression models (see **Methods**) using different set of features were compared by calculating the area under the curve-receiver operating characteristic (AUC-ROC) and the area under-precision recall curve (AU-PRC) values (**fig. 4c**). Models including CS information had higher AUC-ROC and AU-PRC values and slightly improved the performance of the best final model reported in the original article (Ka/Ks + Re/Ks). This improvement was more obvious in the reduced formula (Ka/Ks + Re/Ks + CCSM) and the small range of improvement between full (Ka/Ks + Re/Ks + CCSM) and reduced formulas also agreed with the information reported by Ezoe et al., 2021. The degree of functional divergence (DFD) can be inferred from the best formula by logistic regression analysis. DFD values close to 0 and 1 reflected low (< 0.5) and high (> 0.5) functional divergence, respectively. To enable potential validation of paralogous pairs DFD in upcoming studies and to minimize the erronous assignment of high and low diversified duplicates, we calculated 5% FDR as a threshold. DFD thresholds were 0.93 and 0.46 for high and low diversified pairs, respectively (**fig. 4d**). A table containing labeled genome-wide predictions with additional filters to assist paralogs redundancy experimental verification (see **Methods**)is available at **supplementary table S3**.

In contrast, for the models developed by Cusack et al., 2021 (**fig. 4e-h**) redundancy was categorized into different definitions and a lot of features with distinct transformations were covered. Therefore, we decided to include all the CS metrics to model redundancy for each of the definitions resulting in four different sets: RD4 (extreme redundancy, single mutants have no abnormal phenotype and the double mutant is lethal; without CS information), RD4C (with CS information), RD9 (inclusive redundancy, general definition which also contained RD4; without CS information) and RD9C (with CS information). The number of variables and the relative importance of the six feature categories in the definitions without CS information mostly confirmed the discoveries in the reference (**fig. 4e**). Very briefly, the ranking from best to worst based on median importance ranks in those categories for RD4/RD9-based models was functional annotation (37/16) > network properties (57.5/64.5) > evolutionary properties (76/110) > gene expression (104/105) > protein properties (145/88) > epigenetic modifications (121/127), while gene expression was the category with the highest number of variables in both cases. These findings validated the reproducibility of the models and guaranteed a rigorous interpretation of the following results. Taking into account RD4C/RD9C-based models, chromatin state category was 6th/2nd in importance rankings and became the first in terms of number of variables for both cases. Thus, potentially indicating that CS information would be more useful when prediciting general rather than extreme redundancy. This idea was further verified when SVM models (see **Methods**) using different sets were compared using AUC-ROC and AU-PRC values (**fig. 4f-g**). While CS data clearly improved prediction for general redundancy, it also reduced the values for the extreme definition. Finally, we detected that the intersection with the highest number of features was common to all sets suggesting that the core predicting power remained constant for all the models and, again, ensuring accurate comparisons (**fig. 4h**).

Collectively, we revealed that CS information could give clues into duplicates general functional divergence corroborated by the replication of two independent previously published models.

## Defining functional genomics conservation score and database content

## Experimental validation of potential divergent duplicates

## Discussion

While this flexible framework provides a consistent definition of chromatin states across multiple genomes, thus making easier direct comparison between them, the “full-stack” approach allows the understanding of the potential epigenomic regulation over several tissues/conditions such as differentiating constitutively active regions (Vu & Ernst, 2022). Therefore, we adopted this holistic approach simplifying genome annotations across tissues and species through a single segmentation annotation to allow future evolutionary epigenomics applications. LECIF approach diverse data conservation

Not replace and wide range of genomic prediction properties for the community. Diversity compared to mammals. thus highlighting plant kingdom epigenomic complexity. Deep and narrow vs shallow and broad - community.

integrative features needed for genomic elements and patterns discovery

Despite these pairs do not pass the stringent threshold, they presented high enough DFD values to be considered high divergent paralogs. We decided to assess AOX redundancy by monitoring root phenotypes under two different stresses, considering previously described roles of these genes in response and retrograde-signalling (cita); 2/5 paralogs are not root expressed, simplifying the system and evaluation in seedling stages.

DB and future of evolutionary epigenomics.

Functional translatation of the predictions and resource to explain complex biological mechanisms