

RESEARCH ARTICLE

Open Access

Genome-wide analysis of histone modifiers in tomato: gaining an insight into their developmental roles

Riccardo Aiese Cigliano^{1†}, Walter Sanseverino^{2†}, Gaetana Cremona¹, Maria R Ecolano², Clara Conicella¹ and Federica M Consiglio^{1*}

Abstract

Background: Histone post-translational modifications (HPTMs) including acetylation and methylation have been recognized as playing a crucial role in epigenetic regulation of plant growth and development. Although *Solanum lycopersicum* is a dicot model plant as well as an important crop, systematic analysis and expression profiling of histone modifier genes (*HMs*) in tomato are sketchy.

Results: Based on recently released tomato whole-genome sequences, we identified *in silico* 32 histone acetyltransferases (HATs), 15 histone deacetylases (HDACs), 52 histone methyltransferases (HMTs) and 26 histone demethylases (HDMs), and compared them with those detected in *Arabidopsis thaliana*, maize (*Zea mays*) and rice (*Oryza sativa*) orthologs. Comprehensive analysis of the protein domain architecture and phylogeny revealed the presence of non-canonical motifs and new domain combinations, thereby suggesting for HATs the existence of a new family in plants. Due to species-specific diversification during evolutionary history tomato has fewer HMs than *Arabidopsis*. The transcription profiles of *HMs* within tomato organs revealed a broad functional role for some *HMs* and a more specific activity for others, suggesting key *HM* regulators in tomato development. Finally, we explored *S. pennellii* introgression lines (ILs) and integrated the map position of *HMs*, their expression profiles and the phenotype of ILs. We thereby proved that the strategy was useful to identify *HM* candidates involved in carotenoid biosynthesis in tomato fruits.

Conclusions: In this study, we reveal the structure, phylogeny and spatial expression of members belonging to the classical families of HMs in tomato. We provide a framework for gene discovery and functional investigation of *HMs* in other *Solanaceae* species.

Keywords: *Solanum lycopersicum*, Epigenetics, Development

Background

Chromatin is characterized by a dynamic multi-level organization passing through the nucleosomal basic unit, the 30-nm fiber, and higher-order folding up to the chromosome [1]. Nucleosome remodeling, histone post-translational modifications (HPTMs), DNA methylation, and other factors contribute to define different chromatin states which drive transcription and other chromatin-based nuclear processes [2-4]. In particular, HPTMs correlate

largely with transcriptional regulation, but they are also involved in DNA replication, histone deposition, and DNA repair and recombination. HPTMs occurring in core histone tails include a variety of covalent modifications including acetylation, methylation, phosphorylation, and ubiquitination [2]. Histone acetylation is a reversible process carried out by two classes of enzymes known as histone acetylases (HATs) and histone deacetylases (HDACs) acting on the ϵ -amino group of lysine residues in histones. The acetylation targets in the H3 tail are lysine (K) residues 9, 14, 18 and 23, and in H4 lysine (K) residues 5, 8, 12, 16 and 20 [5].

* Correspondence: marconsi@unina.it

†Equal contributors

¹CNR, National Research Council of Italy, Institute of Plant Genetics, Research Division Portici, Via Università 133, 80055, Portici, Italy

Full list of author information is available at the end of the article

HATs and HDACs are classified into different families that are generally conserved in eukaryotes, including yeast, animals, and plants. Plant HATs are currently categorized into four groups on the basis of homology with other eukaryotic HATs and domain composition: (i) HAG with Acetyltransf_1 domain (PF00583) (AT1) include GCN5-, ELP3-, HAT1-like acetyltransferases; (ii) HAM with a MYST (MOZ-YBF2/SAS3-SAS2-TIP60) domain; (iii) HAC with similarity to p300/CREB-binding protein; (iv) HAF related to the TATA binding protein-associated factor 1 [6]. Specific HATs acetylate H4K5 (HAM members), H4K12 and H3K14 (HAG members). Other acetylation marks, including H3K9, are likely to result from the activities of HAC members with broad specificity [7]. Plant HDACs are grouped into three families: RDP3/HDAC1, hereinafter named HDAs, SIR2 and HD2. Two of these families are homologous to HDACs found in yeast and animals while the HD2 family appears to be unique to plants and unrelated to the other families [6]. Of all HPTMs, acetylation has the most potential to unfold chromatin since it neutralizes the basic charge of the lysine [2]. In the histones, HDACs remove acetyl groups added by HATs by resetting the chromatin structure for the transcription. Furthermore, HDACs and HATs can function in protein complexes as transcriptional co-repressors and co-activators [8-10] or associated with chromatin remodelers as modulators of the accessibility of DNA to different machineries.

In Arabidopsis, HDACs and HATs are emerging as crucial players in growth and development processes, including meiotic recombination, embryogenesis, flowering, and senescence as well as in responses to environmental cues [11,12]. While histone acetylation is dynamically regulated by HATs and HDACs, histone methylation is balanced by the activities of histone methylases (HMTs) and histone demethylases (HDMs) [13]. Plant histone methyltransferases are assigned to different protein groups based on sequence similarity with SET domains (SDG) found in *Drosophila* SU(VAR)3-9, Enhancer of Zeste E(z), Tritorax (TRX), and absent, small, or homeotic discs (ASH1). These proteins function in covalent addition of one (me1), two (me2) or three (me3) methyl groups to lysine residues in histone tails H3K4, H3K9, H3K27, H3K36, and H4K20. Arabidopsis SU(VAR)3-9 members have H3K9 methyltransferase activity and play a key function predominantly in heterochromatin formation and gene silencing [14-18]. Enhancer of Zeste E(z) proteins catalyze H3K27 trimethylation and are involved in the repressive control of gene expression [19]. TRX proteins mediate H3K4 methylation and are required for transcriptional gene activation as well as ASH1 proteins that have a dual methyltransferase function for both H3K4 and H3K36 [20]. Histone methylation occurs also at the arginine residues and is catalyzed by protein arginine

methyltransferase (PRMTs) [21]. Arabidopsis histone methyltransferases and their importance in relation to plant development have recently been reviewed [22]. Histone methylation has long been regarded as an irreversible mark until the discoveries in mammals of two families of HDMs, KDM1 (histone lysine demethylase 1) also known as lysine-specific demethylase 1 (LSD1) and the JmjC domain (Jumonji C) containing proteins [23]. Arabidopsis homologs of human LSD1 act to reduce the level of H3K4 methylation. They were discovered at the level of floral repressor *FLOWERING LOCUS C (FLC)*, a key component of a regulatory network that controls the timing of the start of flowering [24]. The JmjC proteins are able to remove the methyl group on H3K4, H3K9, H3K27 and H3K36 [25,26]. Unlike KDM1, these proteins could reverse all the states (me1, me2, me3) of lysine methylation [21,27-29]. Furthermore, a member of the JmjC proteins has been shown to demethylate arginine H3R2 and H4R3 in animal cells [30]. However, arginine demethylase activity remains to be determined in plants. Recent studies have revealed a role for Arabidopsis JmjC proteins in several aspects of plant development such as floral transition [26,28,29], gametophyte function [31], and circadian rhythm [32,33].

In spite of the crucial role emerging for epigenetic modifications in plant growth and development, little is known regarding HMs in the important crop *Solanum lycopersicum*. Using the complete sequence of tomato genome as well as transcriptomes at different stages/organs [34] we investigated *HM* genes through a bioinformatic approach. In this study we give a comprehensive overview of the structure, phylogeny and spatial expression of members belonging to the classical families of HMs in tomato. Furthermore, we shed light on the position of *HMs* on the tomato genome. We combined this information and *HM* expression profiles with the phenotype of tomato introgression lines (ILs) in order to identify candidate genes involved in epigenetically regulated processes.

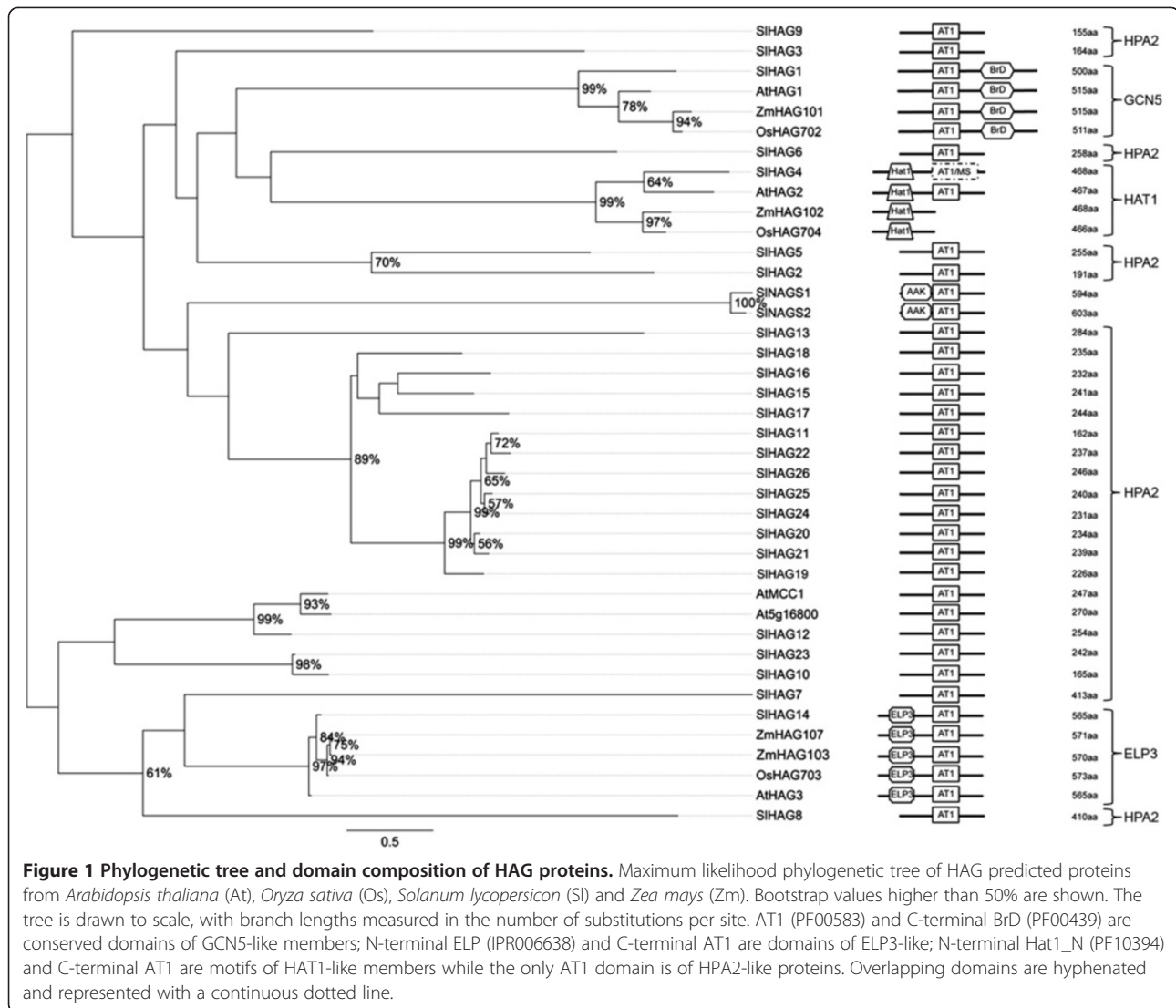
Results and discussion

In this study, 124 histone modifiers (HMs) were identified in tomato. We systematically classified 32 proteins belonging to HATs, 14 to HDACs, 52 to HMTs, and 26 to HDMs.

Tomato HATs

HAGs

The tomato genome encodes 26 proteins showing similarity to the HAG group (Figure 1). One protein (SIHAG14) was found related to the ELP3 family and one (SIHAG4) to the HAT1 family. SIHAG4, in addition to the AT1 domain, also has a MOZ_SAS motif (PF01853) that is typical of MYST acetyltransferases (HAMs) [35]. To date, this combination of domains was never reported. As regards the GCN5



family, no member appears to have been revealed in tomato by preliminary BLAST interrogation. However, a domain-based search allowed us to identify SIHAG1, carrying a C-terminal BrD domain (PF00439) at the 3'-end of Solyc10g045400, as a member of this family. Two other proteins, Solyc02g092260 (SINAGS1) and Solyc03g043950 (SINAGS2), identified by domain analysis as plant HAGs, are unlikely histone acetylases. In fact, in addition to AT1 they have an AAK domain (PF00696) that characterizes proteins involved in aminoacid synthesis [36]. Interestingly, we found another family corresponding to HPA2-like HAGs thought previously to be specific to fungi [6]. The tomato HPA2 family includes most HAGs, namely 23 members, SIHAG2, SIHAG3, SIHAG5 to SIHAG13, and SIHAG15 to SIHAG26.

In order to infer the phylogenetic history of tomato HAGs, we compared them with Arabidopsis, maize and rice orthologs. HAGs are distributed in six main clades

with high bootstrap values (Figure 1), three of which include monocots and dicots while the other three include only dicots. Each clade contains one tomato HAG family, except HPA2 whose members are split into two clades. Interestingly, a subclade of HPA2 members includes eight genes (*SIHAG11*, *SIHAG19-22*, *SIHAG24-26*) that are all closely localized on chromosome 8 in a cluster of about 82 Kb. This finding suggests that the ancestral locus experienced a series of tandem duplication events.

The existence of so many HAG members in the tomato proteome compared with Arabidopsis as well as monocots led us to investigate HAGs in Arabidopsis in greater depth. BLAST search using the AT1 domain as a query returned 33 proteins in Arabidopsis, thereby giving a number close to tomato. Based on the domain composition, in Arabidopsis we identified At2g22910 and At4g37670 which in addition to AT1 have the AAK domain (PF00696). Similarly to tomato, it is likely that

these two proteins are not histone acetylases. Phylogenetic analysis of tomato and Arabidopsis HAGs indicates that the different subgroups evolved differently in these species (see Additional file 1). For example, gene duplication events giving rise to the subgroup including SIHAG19 to SIHAG26 likely occurred only in tomato while the orthogroup that comprises SIHAG6 appears to have experienced an expansion only in Arabidopsis.

As mentioned above, SIHAG4 is a peculiar HAG, having both the typical HAT1_N domain and an MOZ_SAS domain. In order to understand the origin of this combination of domains, we performed extensive research through Interpro (www.ebi.ac.uk/interpro) into the genomes of fully sequenced organisms (<http://www.ncbi.nlm.nih.gov/sites/genome>) and particularly in plants (www.phytozome.org). Intriguingly, a domain structure similar to that of SIHAG4 was found mostly in plants and additionally in the brown alga *Ectocarpus siliculosus* (Chromalveolata) and in *Trichoplax adhaerens* (Animalia). The existence of SIHAG4-like proteins in different organisms suggests that histone acetylases with both HAT1_N and MOZ_SAS domains can be categorized as members of a new family which we name GNAT/MYST-Like (GML).

Additional file 2 shows the proteins with the highest similarity to SIHAG4. Out of 32 species belonging to Plantae, 12 evidenced proteins with both HAT1_N and MOZ_SAS domains. Interestingly, these species are not randomly distributed among the different orders. Indeed, GML proteins seem to be lacking in *Brassicales*, *Poales*, *Ranunculales* and *Volvocales*, although the scant sequence data suggest caution regarding this finding. The distribution of GML proteins in Planta, Animalia and in Chromalveolata suggests that the combined domains AT1 and MOZ_SAS occurred early on in evolutionary history. However, most of the organisms show HAT1_N and MOZ_SAS domains in two functional distinct families, GNAT and MYST histone acetylases, respectively. Due to lack of information about the biological function of GML proteins, we can only speculate that the separation of the two domains could confer an advantage for nuanced control of the histone acetylation level in the genome.

To address the question of the possible function of tomato HAGs we examined their expression profiles in several organs (Figure 2). Given the wide range of expression values, we categorized the tomato HAGs in three groups of low (Figure 2A), middle (Figure 2B) and high expression (Figure 2C). Among low-expressed members, *SIHAG11* and *SIHAG17* did not show any preferential expression in the analyzed organs as compared to the other members that might have a different function. *SIHAG8* and *SIHAG22* could play a role in vegetative development, and by contrast *SIHAG18* and *SIHAG6* in reproductive development. The middle-expressed group of genes evidenced broad-ranging activities, except *SIHAG15* and *SIHAG19* which are

strongly expressed in leaves and roots, respectively. The expression profiles in the group of high-expressed members suggest a wide functional role for some HAGs (*SIHAG2*, *SIHAG16*, *SIHAG10*, and *SIHAG25*) in contrast to *SIHAG5* and *SIHAG21* preferentially expressed in roots and leaves, respectively. The Arabidopsis genome was predicted to encode three HAGs, AtHAG1, AtHAG2 and AtHAG3, which belong to GCN5, HAT1 and ELP3 families, respectively [6]. Interestingly, HPA2-like HAGs also occur in Arabidopsis and one member of this family (AtMCC1) was recently found [37]. In tomato, the closest homologs of AtHAG1/AtGCN5, AtHAG3 and AtMCC1 are SIHAG1, SIHAG14 and SIHAG12, respectively. Such proteins are likely to accomplish specific functions in tomato as they do in Arabidopsis since their genes show comparable expression profiles in similar organs, except for *AtHAG1/AtGCN5*. In particular, *AtHAG1* plays an essential role in many plant development processes, such as meristem function, cell differentiation, leaf and floral organogenesis, and responses to light and cold [38]. *AtHAG3* is involved in transcription elongation, cell proliferation, leaf axis development, seedling and root growth [39-41], and *AtMCC1* was shown to be involved in flowering time and meiosis [37].

HAMs

The tomato proteome has one MYST acetyltransferase, namely SIHAM1, that is a 477-aa long protein characterized by N-terminal Chromo (PF00385), C2H2 (PF00096), and C-terminal MOZ_SAS (PF01853) domains, that are typical of class I HAMs [35]. Previous studies have shown that other plant HAMs belong only to the class I [35]. Phylogenetic analysis (see Additional file 3) shows that HAMs are distributed in two clades, one of which includes tomato as well as Arabidopsis proteins. The other clade contains two proteins from monocots, maize and rice. This separation indicates that a single ancestral HAM gene gave rise to HAMs in monocots and dicots, being a specific event of duplication at the origin of the expansion of this family in Arabidopsis and maize. The expression pattern of *SIHAM1* shows that it is expressed in all the examined organs with the highest expression in flowers and in 3 cm fruit (Figure 2). Latrasse and colleagues [35] found that *AtHAM1* and *AtHAM2* are strongly expressed in flowers and act redundantly in male and female gametophyte development. This evidence suggests that *SIHAM1*, in addition to its putative role in seed and/or fruit development, could play a role in gametogenesis like the Arabidopsis ortholog.

HACs

The present survey identified four proteins belonging to the HAC group in tomato (SIHAC1 to SIHAC4). As shown in Figure 3A, the domain composition of HACs is variable but all share the typical domains of this class [6]. Tomato HACs are included together with Arabidopsis

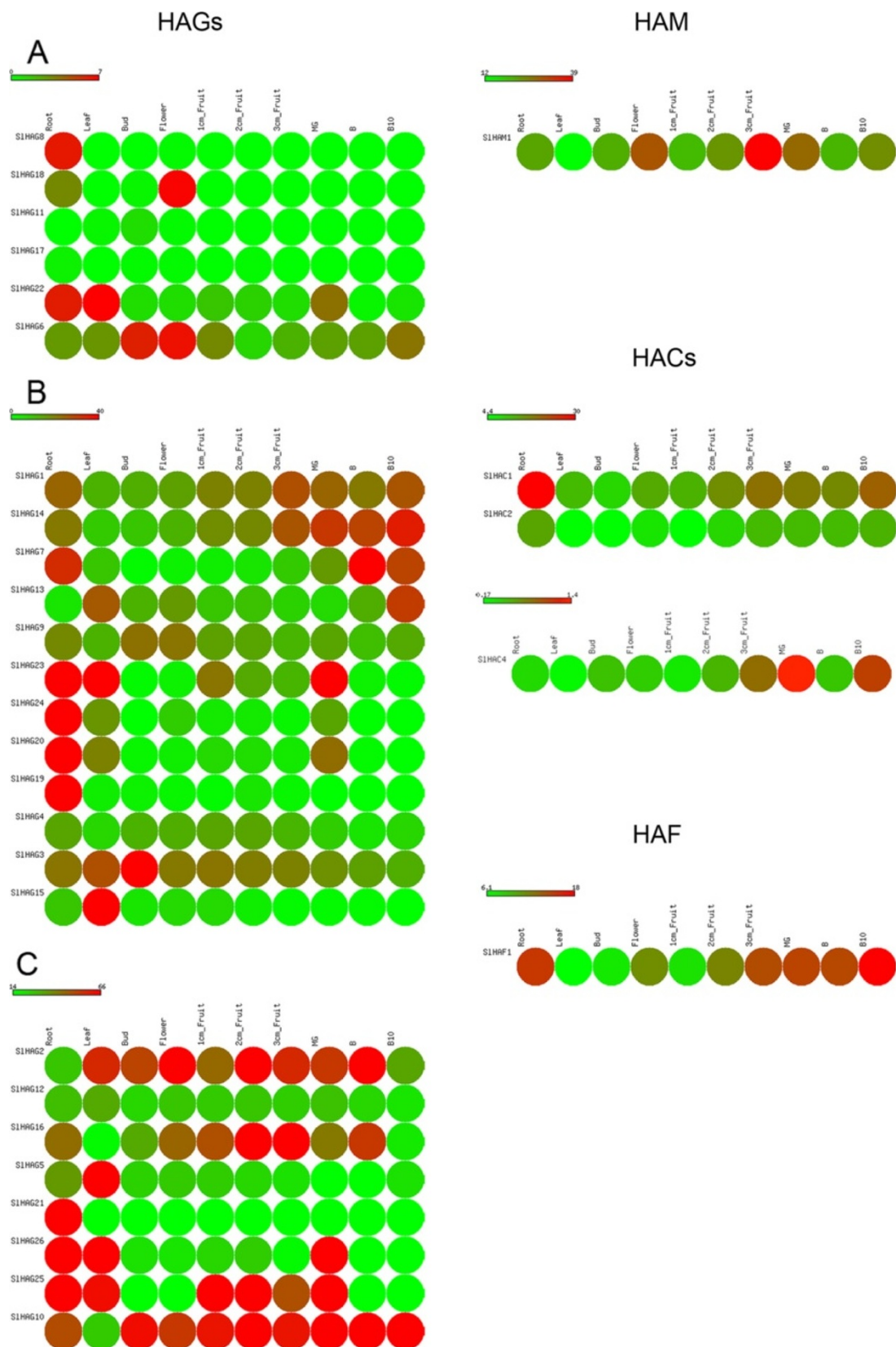


Figure 2 (See legend on next page.)

(See figure on previous page.)

Figure 2 Expression profiles of tomato HATs. Heat map of RNA-seq expression data from root, leaf, bud, flower, 1cm_fruit, 2cm_fruit, 3cm_fruit, mature green fruit (MG), berry at breaker stage (B) and berry ten days after breaking (B10). HATs with low, middle and high expression values are reported in **A**, **B** and **C**, respectively. The expression values are measured as reads per kilobase of exon model per million mapped reads (RPKM).

HACs in two main clades separated from the clade containing HACs of rice and maize lacking the ZZ-domain (Figure 3A). In the most expanded clade (boxed in Figure 3), the dicots form a distinct group compared with monocots. Overall, data suggest that different gene duplication events gave rise first to the two groups of HACs both in monocots and dicots, and subsequently to the expansion of this family in both phyla. Interestingly, the expansion was slightly larger in Arabidopsis than in tomato.

In order to gain insight into the possible role of tomato HACs, we examined their expression profiles in different tomato organs (Figure 2). *SIHAC4* shows the strongest expression in fruit at different developmental stages. It is interesting that the peak of *SIHAC4* expression occurs in mature green berries and is followed by a strong reduction in fruit at breaker stage, thereby suggesting a role in the transition between these two fruit developmental stages. *SIHAC1* and *SIHAC2*, forming a distinct clade, are the most widely expressed tomato HACs, with the latter showing lower expression values. Similarity between *SIHAC1* and *SIHAC2* in terms of sequence and expression profile in reproductive organs suggests a functional redundancy that is analogously reported for Arabidopsis homologs *AtHAC1/AtHAC5* and *AtHAC1/AtHAC12* [42]. The presence of *SIHAC1* and *SIHAC2* in the same clade of Arabidopsis *AtHAC1*, *AtHAC5* and *AtHAC12* further supports a role of these proteins in tomato reproduction. Indeed, knockdown of *AtHAC1* induced reduced fertility and late flowering [43] and analysis of *hac1/hac5* and *hac1/hac12* double mutants highlighted their role in flowering time in Arabidopsis [42]. *SIHAC3* is likely a pseudogene since it does not appear to be expressed in the tissues under analysis.

HAFs

Tomato proteome has one TAF_{II}250 protein (*SIHAF1*) (Figure 3B) that shows the same domain composition of Arabidopsis, rice and maize HAFs [6]. Phylogenetic comparison with these species evidenced that *SIHAF1* forms a distinct clade with *AtHAF1* and *AtHAF2* separated from *OsHAF701* and *ZmHAF101* (Figure 3B). Interestingly, *SIHAF1*, albeit expressed in all the organs considered, has the strongest expression in roots and in fruit, particularly in berries ten days after breaking, thereby suggesting an important role in fruit maturation (Figure 2).

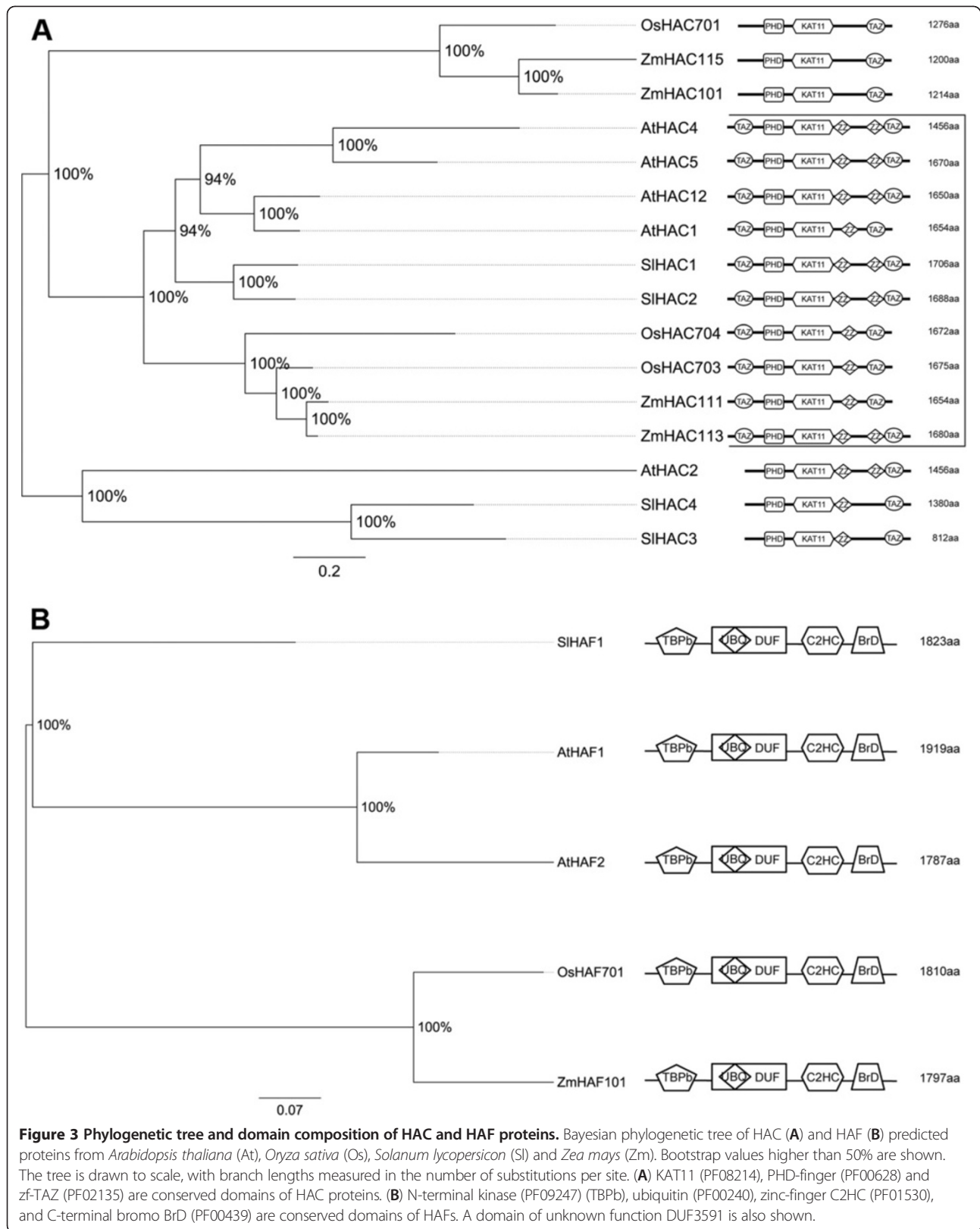
Tomato HDACs

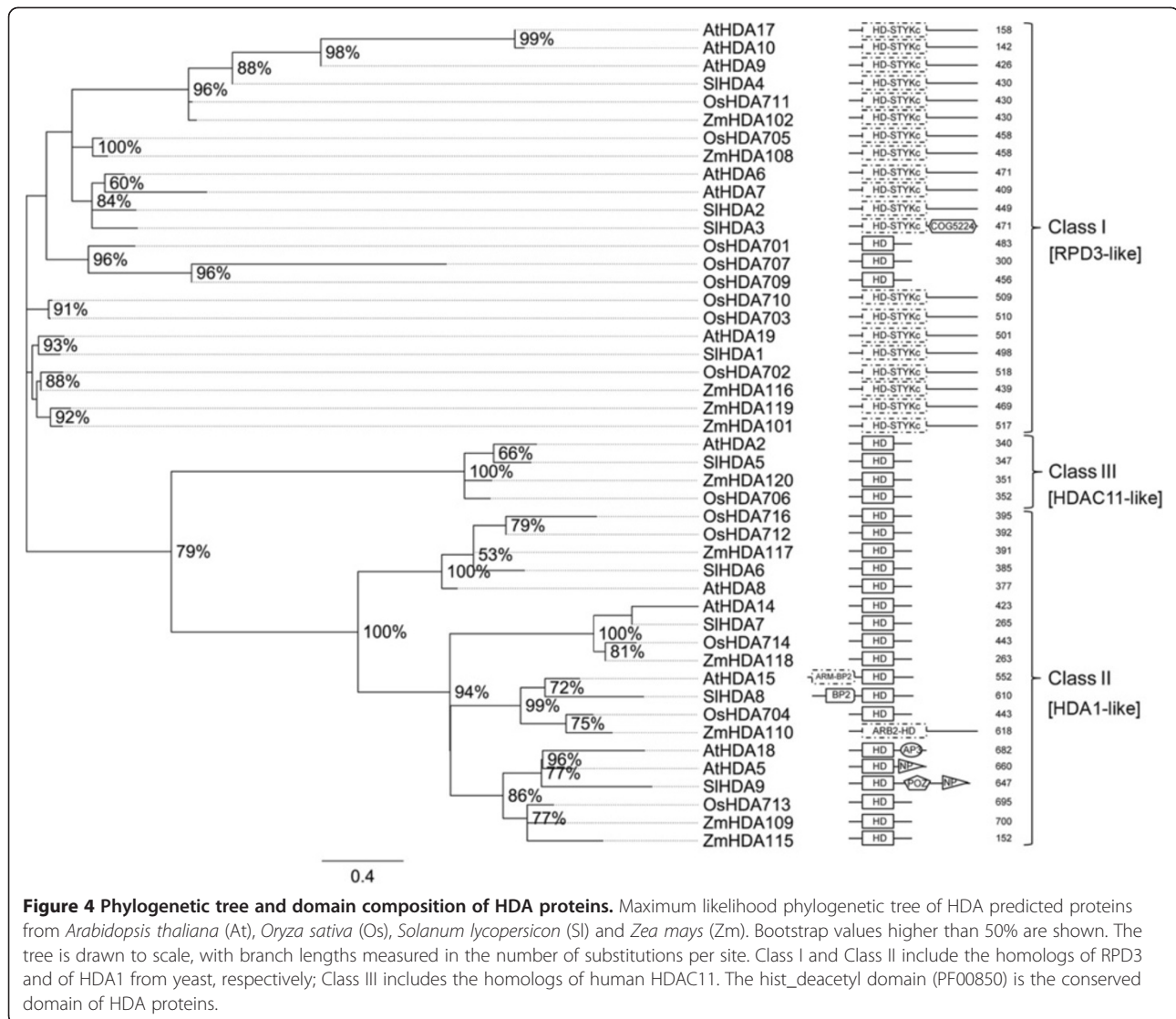
HDA1s

Investigation of the tomato proteome revealed nine RPD3/HDA1 family members. The phylogeny of tomato HDAs

evidences that they cluster with HDAs of Arabidopsis, maize and rice (Figure 4) in accordance with the subdivision of this family into three classes as reported in the literature [6,44]. This family had a higher expansion in monocots, especially in rice, than in dicots where Arabidopsis has the highest number. In addition to the Hist_deacetyl domain (PF00850), new conserved domains were found in tomato HDAs as well as in orthologs of Arabidopsis, rice and maize. Indeed, as shown in Figure 4, Class I SIHDAs have an STYKc domain (SM00221), and a Ser/Thr/Tyr kinase catalytic domain, overlapping with the Hist_deacetyl domain. Moreover, a C-terminal COG5224 domain, which is involved in DNA-binding, is found in *SIHDA3*. As regards Class II, a zf-RanBP domain (PF00641), which binds Ran-GDP involved in nuclear transport, occurred in *SIHDA8* and in *SIHDA9*, and a C-terminal nucleoside phosphorylase domain (NP) together with a POZ domain (PF00651) was found. The presence of the POZ domain, which is a homo/heterodimerizing domain evidenced in histone deacetylase-containing complexes, suggests that *SIHDA9* could take part in a multi-protein complex. The occurrence of BP and NP domains as well as a new domain arrangement (AP3) was also evidenced in Arabidopsis HDAs.

In order to understand the candidate function of tomato HDAs, we looked at their expression profiles (see Additional file 4). Given the wide range of expression values, we categorized the tomato HDAs in three groups having low (see Additional file 4A), middle (see Additional file 4B) and high expression (see Additional file 4C). *SIHDA2* expressed mostly in root and bud is the lowest expressed gene among the tomato HDAs. Its expression profile suggests a role in highly dividing tissues such as root and flower meristems. The middle-expressed HDA members show very different expression profiles. Among them, *SIHDA9* could exert a possible role in root development as supported by its strong expression in this organ and by its similarity to *AtHDA5* and *AtHDA18* [45]. A complementary role of *SIHDA5*, *SIHDA6* and *SIHDA7* in fruit development from 1 cm to B10 stage is suggested by their peaks of expression in these stages. Finally, the highly expressed *SIHDA1* and *SIHDA3* show the strongest expression at B10 and B fruit stages, respectively, thereby supporting a possible role in tomato fruit ripening. *SIHDA1* and *SIHDA3* have respectively a sequence similarity with *AtHDA6* and *AtHDA19* that in Arabidopsis have been linked to flowering, embryo development and other biological processes [11,46,47].





SRTs

In the tomato proteome, we identified two histone deacetylases belonging to the SIR2 family, namely SISRT1 and SISRT2 (see Additional file 5). They are characterized by an SIR2 domain (PF02146) and correspond to LeSRT1105 and LeSRT1104, previously described by Pandey and colleagues [6]. The expression profiles of tomato *SRT* genes evidence expression peaks of *SISRT1* in bud and in 1 cm-sized fruit while *SISRT2* was expressed in flower and in fruit at B10 (see Additional file 4). These findings suggest that *SISRT1* could play a role in the early stages of fruit development as well as in early gamete development whereas *SISRT2* is involved later in both fruit ripening and in gametogenesis. The expression profile of *SISRT2* also supports a role in *FLC* regulation as suggested for *Arabidopsis* counterparts by Bond and colleagues [48].

HDTs

According to the results of Pandey and colleagues [6] who described three HDTs in tomato proteome (HDT1101, HDT1102, HDT1103) we found SIHDT1, SIHDT2 and SIHDT3 corresponding to HDT1102, HDT1103 and HDT1101, respectively (see Additional file 6). SIHDT2 shows a C-terminal zinc finger domain in addition to the predicted HD2 domain (EFWG motif at the N-terminus). The evolutionary history of plant HDTs, including those of tomato, was well illustrated by Pandey and colleagues [6]. As shown in Additional file 4, the preferential expression of tomato *HDTs* occurs at early stages of fruit development. In particular, *SIHDT1* is highly expressed in 1 cm fruit, *SIHDT2* in both 1 cm- and 3 cm-sized fruits, *SIHDT3* in 3 cm fruit and in mature green berries. Overall, these expression profiles suggest a role of tomato *HDTs* in fruit development. Interestingly, tomato *HDTs* seem to be all

closely related to AtHDT3 (see Additional file 6) that was shown to be involved in ABA response and seed germination [45].

Tomato HMTs

SDGs

We identified 43 SET-Domain Group (SDG) proteins in tomato belonging to seven classes like Arabidopsis SDGs according to the classification of Springer and colleagues [49] (Figures 5, 6 and 7). In detail, three proteins, SISDG21, SIDG22 and SISDG23, clustered with class I AtSDGs (AtSDG1, AtSDG5, AtSDG10) that are homologous to E (z) (Figure 5A). Although SISDG21 and SISDG22 show similar domain architecture to Arabidopsis class I SDGs,

they have an additional SANT domain, while SIDG23 has lost the two conserved EZDs (enhancer of zeste domains). Ten proteins, SISDG15 to SISDG19 and SISDG33 to SISDG37, cluster with five Arabidopsis proteins annotated as homologs to ASH1 (class II) (Figure 5B). The expansion of this class in tomato likely arose from gene duplications generating also pseudogenes (see below). Tomato SISDG15, SISDG16, SISDG19, SISDG33 to SISDG35, SISDG37 show a domain arrangement similar to Arabidopsis members while SDG17, SDG18, and SDG36 lack conserved domains of this class. Six proteins (SISDG20, SISDG24-26, SISDG29, SISDG44, previously described as SITX1 by Sadler et al. [50]) belong to class III of SDGs (Figure 6A), being homologous to TRITHORAX (TRX). They have

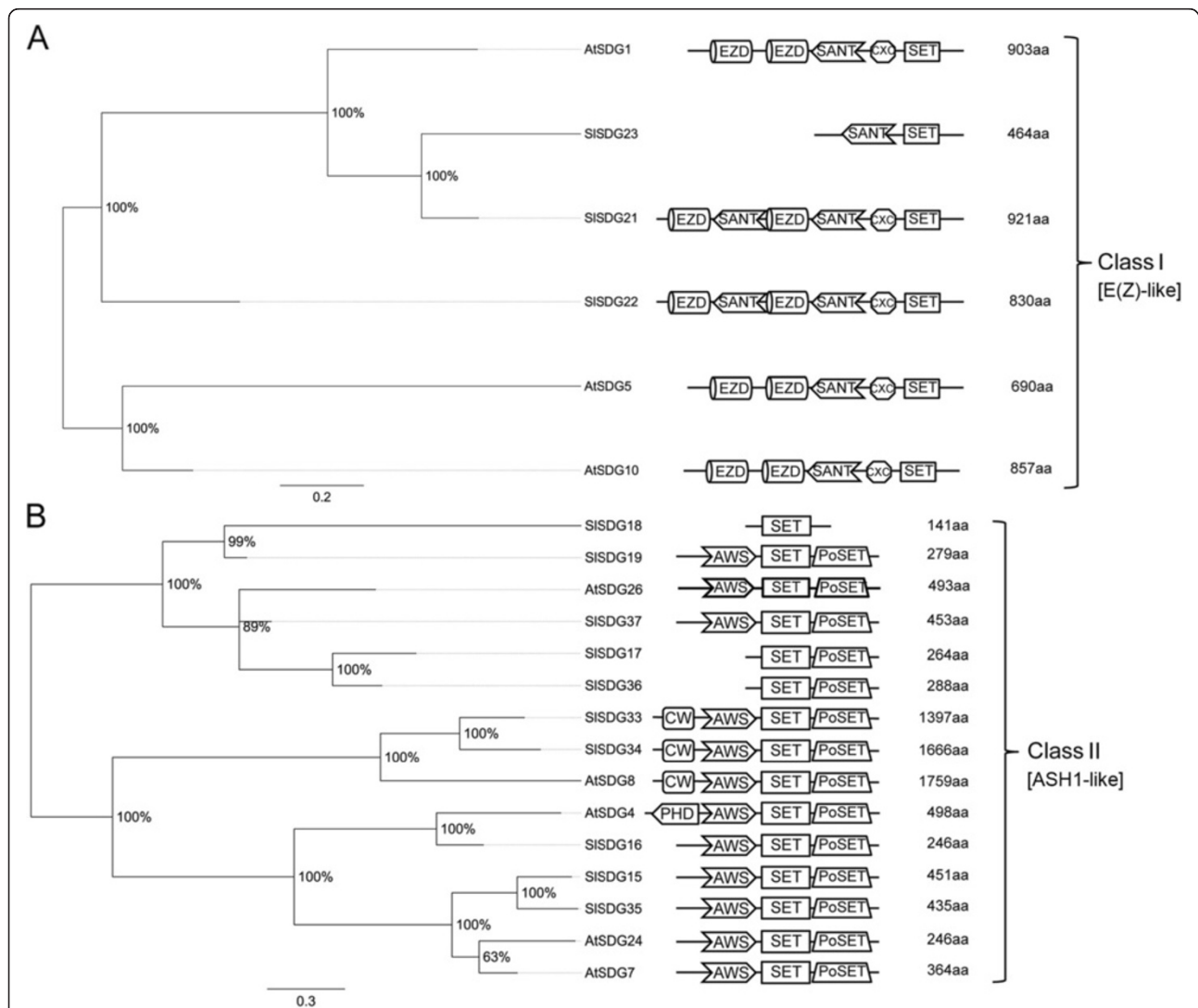
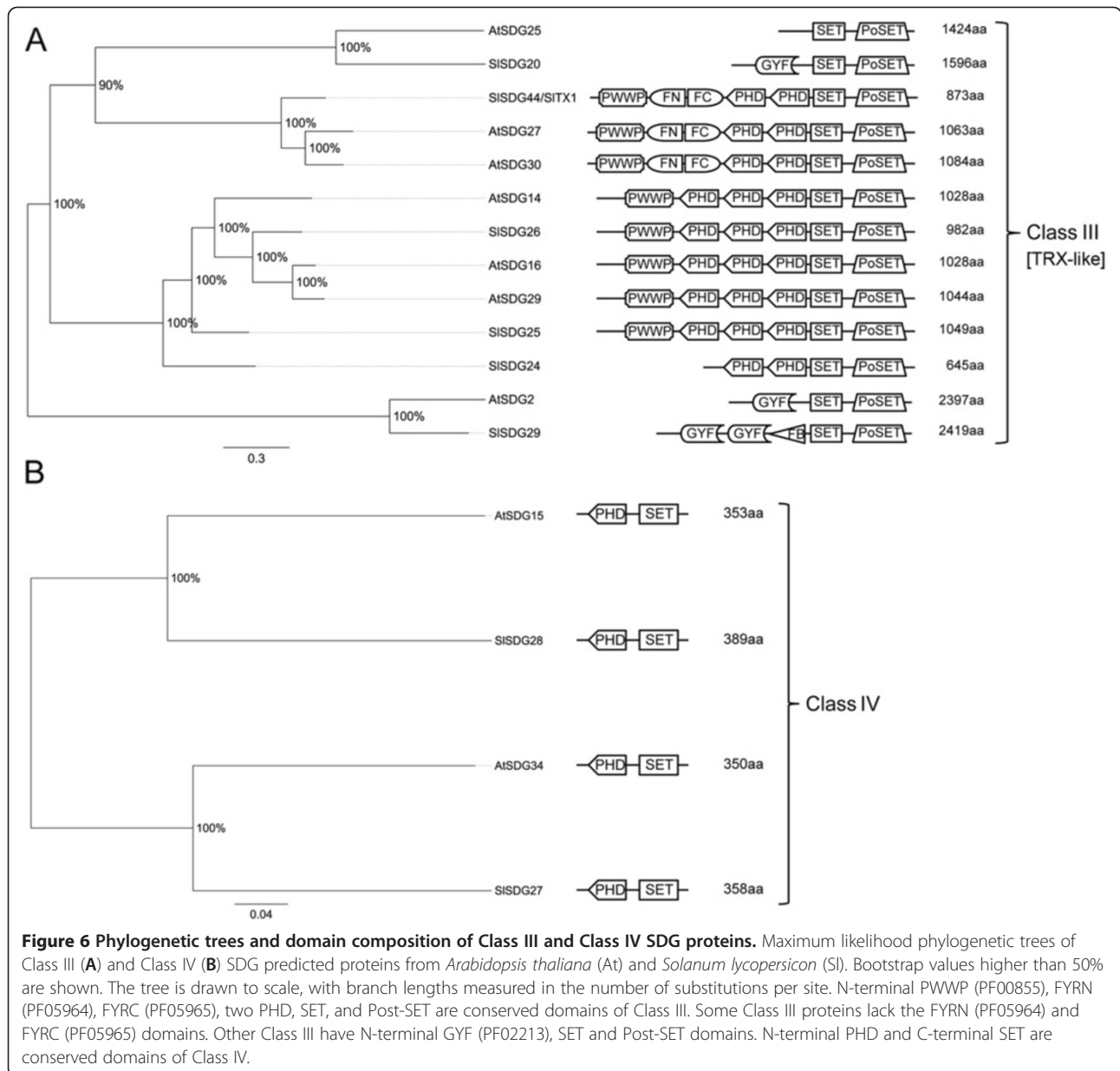


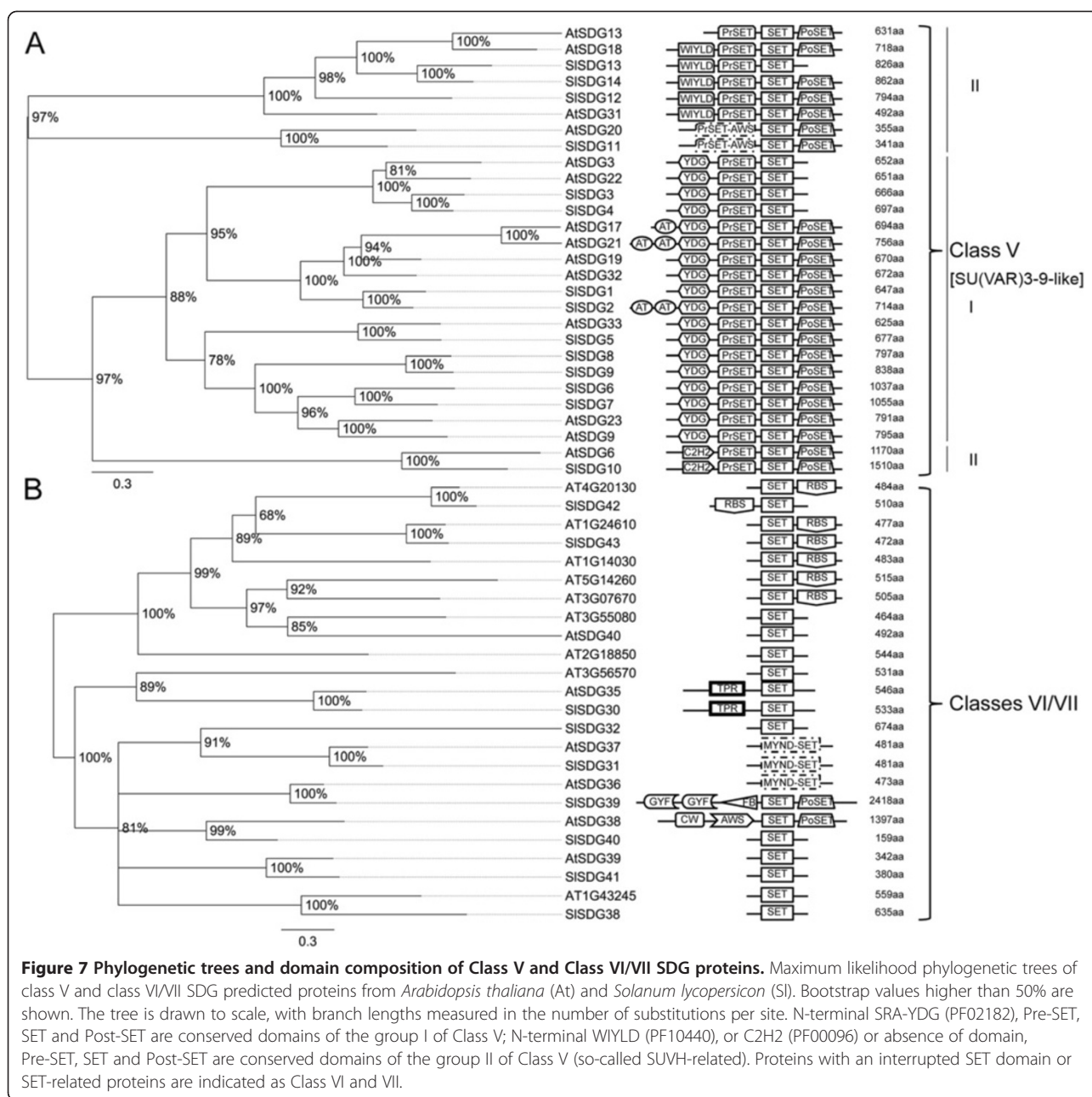
Figure 5 Phylogenetic trees and domain composition of Class I and Class II SDG proteins. Maximum likelihood phylogenetic trees of Class I (A) and Class II (B) SDG predicted proteins from *Arabidopsis thaliana* (At) and *Solanum lycopersicon* (Sl). Bootstrap values higher than 50% are shown. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site. Two E(Z), SANT (SM00717), CXC (PF03638), and SET (PF00856) are conserved domains of Class I. N-terminal AWS (SM00570), SET and Post-SET (SM00508) are conserved domains of Class II. The PHD domain (PF00628) and CW domain (SM00605) are also found in Class II proteins.



the same domain architecture (SlSDG44, SlSDG25-26) as their *Arabidopsis* counterparts or a GYF and F-box (SlSDG29) in addition to the SET and Post-SET domains. Moreover, we found that tomato as well as *Arabidopsis* has proteins with three PHD domains, contrasting with findings previously reported in *Arabidopsis* [49]. SlSDG24 has two PHD domains but one seems to be truncated at the N-terminus because it lacks the PWWP domain. Two TRX-related proteins (SlSDG27 and SlSDG28) belong to class IV SDGs (Figure 6B). This class includes proteins only present in yeast and plants [49]. Fourteen tomato SDGs (SlSDG1 to SlSDG14) belong to class V (Figure 7A). These are homologous to SU(VAR)3-9 and are distributed in two main clades containing members of the first or

second subgroup of this class [49]. Some members lack the Post-SET domain and others gain AT-hook domains as the closest *Arabidopsis* orthologs. Seven members (SlSDG30-32, SlSDG38-43) cluster within class VI and two within class VII of SDGs (Figure 7B). These classes include proteins with an interrupted SET domain or SET-related proteins. The domain architecture of tomato and *Arabidopsis* members belonging to these classes is quite similar, except SlSDG39 which shows a domain composition typical of Class III SDGs.

In order to gain insights into the biological role of tomato SDGs, we analyzed their expression profiles by grouping SDGs according to their class (Figure 8). SlSDG23 and SlSDG21 (Class I) have similar expression



profiles, being mainly expressed in root, bud and fruit up to 3 cm, while *SISDG22* is mostly expressed in 2 cm fruit up to B stages. On the basis of these expression profiles we could argue that the first two genes play redundant roles in root and fruit development and *SISDG22* is likely to be more specific to the later stages of fruit maturation.

As regards class II SDGs, some genes with very specific peaks of expression may be noted. Indeed, *SISDG35* is strongly expressed in leaves, *SISDG34* in fruit at the 3 cm stage, *SISDG17* in flowers, and *SISDG19* in buds. These expression profiles suggest a possible wide

subfunctionalization of class II SDGs in tomato with a low degree of redundancy. A role in fruit development could be played by *SISDG33* with an expression profile similar to *AtSDG8* [51] which regulates gene expression in the carotenoid pathway [52]. *SISDG16* is mostly expressed in buds and in the early stages of fruit development. Interestingly, this gene could share some functions with its Arabidopsis counterpart, *AtSDG4*. Indeed, the latter mainly expressed in pollen is involved in pollen tube growth and reproduction in Arabidopsis [53]. *SISDG18* and *SISDG36* were noticed to behave like pseudogenes, not being expressed in any of the organs analyzed.

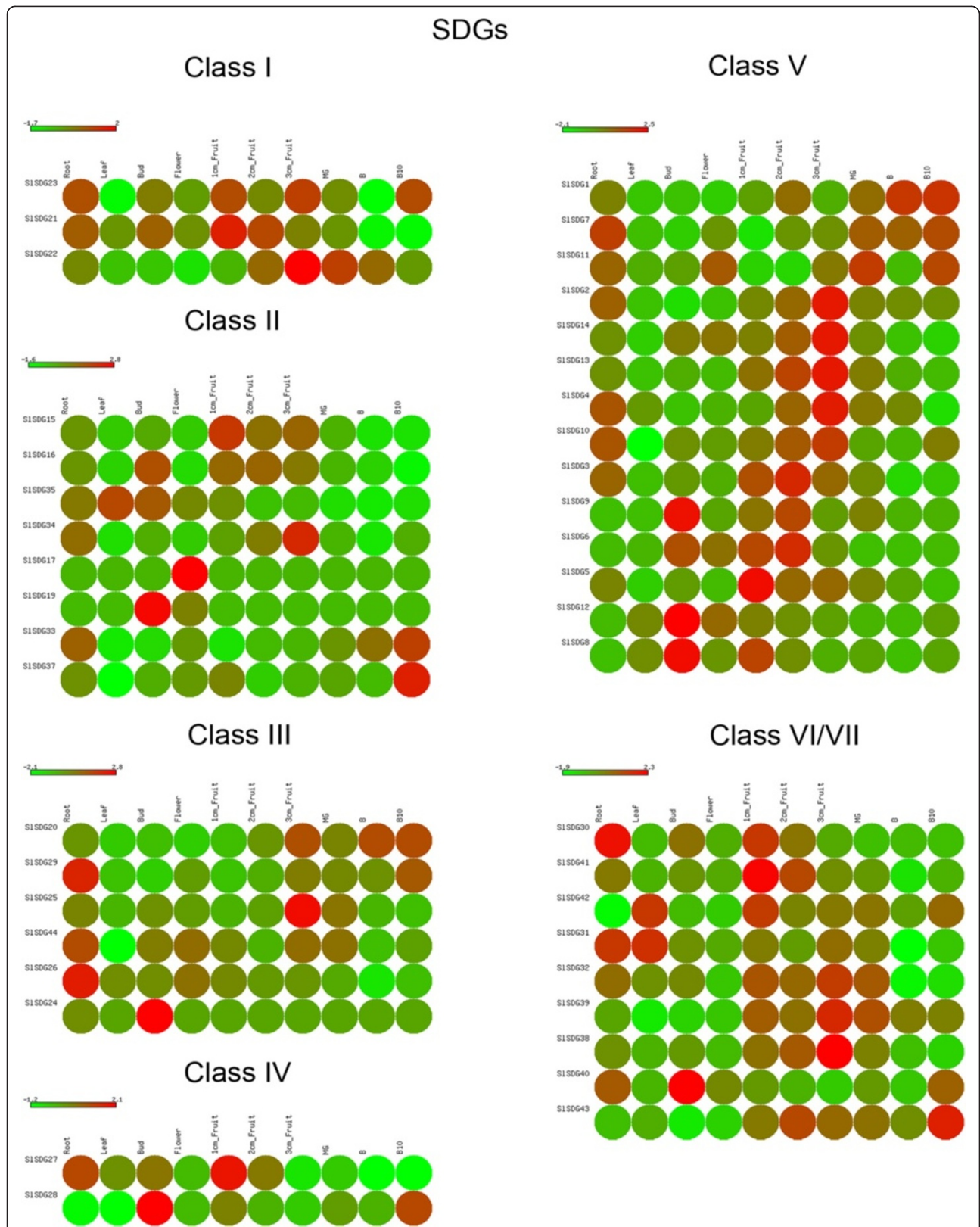


Figure 8 Expression profiles of tomato SDGs. Heat map of RNA-seq expression data from root, leaf, bud, flower, 1cm_fruit, 2cm_fruit, 3cm_fruit, mature green fruit (MG), berry at breaker stage (B) and berry ten days after breaking (B10). The expression values are measured as reads per kilobase of the exon model per million mapped reads (RPKM).

Among the class III *SDGs*, *SISDG29*, *SISDG44* and *SISDG26* could play redundant roles in root development, as could *SISDG20* and *SISDG29* in fruit maturation. The latter is closely related to *AtSDG2* which was shown to affect vegetative growth and reproduction in *Arabidopsis* by regulating the expression of hundreds of genes [54,55]. Moreover, the expression profile of *AtSDG2* [51] is similar to that of *SISDG29* in comparable organs, thereby supporting the idea of similar functions. *SISDG44* is related to *AtSDG27* that was shown to regulate the expression of a xyloglucanase [56] which belongs to a class of enzymes involved in tomato fruit ripening [57]. In a similar fashion, *SISDG44* could act in fruit ripening since it is highly expressed in fruits, particularly at the MG stage. On the contrary, some degree of functional divergence seems to have occurred between *SISDG20* and its homolog *AtSDG25* involved in flowering time in *Arabidopsis* [58]. Indeed, the latter is more expressed in flowers while *SISDG20* is very poorly expressed in this organ.

The two members of tomato Class IV *SDGs* have different expression profiles: while *SISDG27* is strongly expressed in roots and fruit at the 1 cm stage, *SISDG28* is mostly expressed in buds and in fruit at the B10 stage. These differences suggest that the two genes evolved different functions, with *SISDG28* being mainly involved in reproduction.

Tomato *SDGs* of class V may show a high degree of redundancy in some functions. Indeed, *SISDG3*, *SISDG9*, *SISDG6* and *SISDG5* have their highest expression in fruit at 1 cm and 2 cm, *SISDG2*, *SISDG14*, *SISDG13*, *SISDG4* and *SISDG10* have their peak expression in fruit at the 3 cm stage, while *SISDG1* and *SISDG7* are particularly expressed in fruit at MG up to B10 stages. Therefore, these expression profiles suggest that they might play roles in fruit and/or seed at sequential stages of development. Moreover, *SISDG9* is highly expressed in buds as well as *SISDG12* and *SISDG8*, suggesting that they could have a function in meiosis or in flower development.

As with the above-reported *SDGs*, also the members of classes VI and VII may have a possible redundant function. For example, *SISDG30*, *SISDG41* and *SISDG42* are highly expressed in 1 cm fruit while *SISDG32*, *SISDG39* and *SISDG38* in 3 cm fruit, thereby suggesting sequential functions in embryo/fruit development. A more specific expression profile is shown by *SISDG40* which evidenced peak expression in the bud, indicating a role in gamete and/or flower development. However, the putative involvement of these genes in development has not been investigated in any plant species.

PRMTs

We identified nine PRMTs in tomato (*SIPRMT1* to *SIPRMT9*). *SIPRMT8* was already described by Krause and colleagues [59] and was named PAM1.1. Specific patterns

in the catalytic AdoMet_Mtase domain (CD02440) [59] allowed us to categorize *SIPRMT1*, 2, 3, 5, 7, and 9 as class I PRMTs while *SIPRMT4* and *SIPRMT6* belong to class II (see Additional file 7). For class I some duplication events were highlighted in dicot species.

The expression profiles of tomato *PRMTs* (see Additional file 8) suggest functional redundancy among these genes since some organs are characterized by two or more *PRMTs* with high expression levels. This is the case of roots where *SIPRMT9*, *SIPRMT7* and *SIPRMT3* have their relative strongest expression. *SIPRMT8*, *SIPRMT2*, and *SIPRMT5* were expressed in fruit at the 1 cm stage while *SIPRMT4* and *SIPRMT1* at the B10 stage. To investigate the biological function of *SIPRMTs*, we considered the role of orthogroups in *Arabidopsis*. *SIPRMT5* and *SIPRMT8* belong to the same clade as *AtPRMT11* and *AtPRMT12*. The latter were suggested to be in the same histone methylation complex on the basis of their physical interaction [60] and spatial expression profiles. By contrast, *SIPRMT5* and *SIPRMT8* have quite different expression profiles and, when similar organs are compared between the two species, only the first has a profile resembling that of *Arabidopsis* counterparts. On this basis, we hypothesize that *SIPRMT5* and *SIPRMT8* evolved independent functions, with *SIPRMT5* perhaps retaining the biological role of *AtPRMT11* and *AtPRMT12*. If this is true, *SIPRMT5* should be involved in flowering time, flower morphology and fertility as well as in leaf development [61]. *SIPRMT7* is the closest homolog to *AtPRMT10* which was shown to be a component in the autonomous pathway which controls the floral transition in an FLC-dependent manner [62]. Since the expression profiles of these two genes are comparable, *SIPRMT7* might also have a functional role in flowering time. *SIPRMT3* and *SIPRMT9* grouped with *AtPRMT13* and *AtPRMT14* that were shown to redundantly control the floral transition [63]. Accordingly to their functional redundancy, *AtPRMT13* and *AtPRMT14* have very similar expression profiles. On the other hand, *SIPRMT3* and *SIPRMT9* differ greatly in expression profile, also vis-à-vis their *Arabidopsis* counterparts, when similar organs are compared [51]. *SIPRMT3* and *SIPRMT9* could play different roles in tomato development and might not be involved in flowering time. *SIPRMT6* is the closest homolog to *AtPRMT5*, which was shown to be involved in vegetative growth and flowering time [64,65]. The different expression profiles of *AtPRMT5* [51] and *SIPRMT6* suggest that the latter evolved a different role possibly in fruit maturation as evidenced by its expression peak in fruit at the MG stage.

Tomato HDMs

HDMA5

In tomato, we identified 34 proteins showing similarity to HDMA histone demethylases. All are characterized by the C-terminal Amino_Oxidase domain (AOD) (PF01593)

but only six (SIHDMA1 to SIHDMA6) also have the N-terminal SWIRM (PF04433) domain that is conserved in all HDMA. As shown in Additional file 9, HDMA proteins are distributed in two main clades, comprising one (SIHDMA6) and five tomato members (SIHDMA1-5). Phylogenetic analysis suggests that four ancestors gave rise to the present number of *HDMA*s in tomato, and accordingly at least two events of gene duplication increased the number of *HDMA*s from four to six. In particular, *SIHDMA1*, 2 and *SIHDMA4*, 5 could have been arisen from a tandem duplication event as suggested by their close position on chromosome seven (not shown).

The Additional file 10 shows the expression profile of tomato *HDMA*s, divided into three groups with low (A), mild (B) and high (C) expression. *SIHDMA2* is barely detectable in buds and in fruit from 2 cm stage to B, while *SIHDMA5* is mostly expressed in buds and flowers, suggesting a major role of the former gene in fruit development and the latter gene in gamete and/or flower development. *SIHDMA4* and *SIHDMA6* are detectable in all organs, pointing out a possible role for these genes throughout development including reproductive stages. *SIHDMA1* is quite uniformly expressed in all plant organs and *SIHDMA3* has a clear preferential expression in fruit from 2 cm stage to B10. Collectively, these profiles indicate that tomato *HDMA*s could play redundant roles in different aspects of fruit development and *SIHDMA3* could be the major histone demethylase in tomato. Moreover, *SIHDMA3* could play a role both in flowering time and root elongation, as suggested by its expression profile and its sequence similarity to AtHDMA3 [66,67].

JMJs

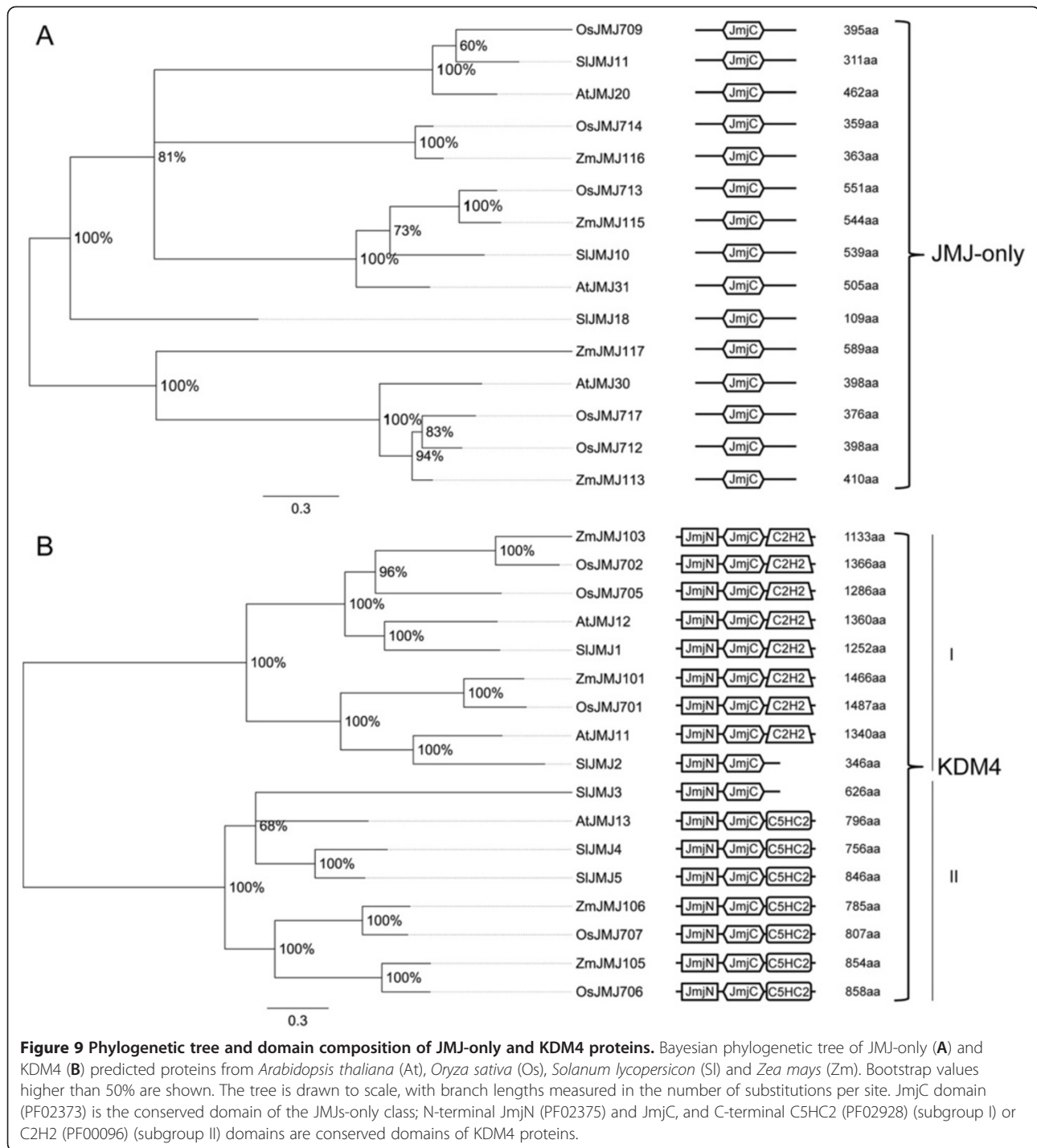
The tomato proteome reveals 20 proteins belonging to the JMJ family of HDMA. On the basis of their domain composition we classified them in five classes that take their names from their human counterparts: JMJC-only, KDM4, JMJD6, KDM5 and KDM3 [68]. The tomato JmjC-only class includes three proteins (SIJM10-11, and SIJM18), the KDM4 class five proteins (SIJM1-5), and KDM5 class four proteins (SIJM6-8, and SIJM16). The classes JMJ6 (SIJM9 and SIJM12) and KDM3 (SIJM13-15, SIJM17, and SIJM19-20) include two and six members, respectively.

The evolutionary history of JMJs was inferred by comparing these proteins in tomato, Arabidopsis, maize and rice (see Additional file 11). Interestingly, a domain-based search led us to identify four new JmjC-only (ZmJM113, ZmJM115-117), two JMJD6 (ZmJM114 and ZmJM118) and one KDM3 (ZmJM112) proteins in the maize proteome that were absent in the ChromDB and were included in our analysis. As shown in Additional

file 11, HDMA are distributed in five main clades, all of which include tomato proteins. Three clades contain exclusively members of classes KDM3, KDM4 and KDM5; the remaining clades contain members belonging both to classes JMJ-only and JMJD6. In the phylogenetic tree (Figure 9A) two main groups of JMJ-only were evidenced, including tomato members in one. This scenario suggests that one ancestor gave rise to the current number of JMJ-only proteins in tomato. All the tomato members included in this class share the same domain architecture with their orthologs. KDM4 class members (Figure 9B) are split into two main clades with two and three tomato proteins. One clade includes the C2HC2-domain proteins and the other the C5HC2 domain proteins [68]. SIJM2 and SIJM3 did not show the same domain architecture as the other KDM4 since the C-terminal domain C2HC2 or C5HC2 is lacking. Two duplication events in tomato as well as in maize and rice expanded the second group, while only an AtJM13 is encoded by the Arabidopsis genome. The JMJD6 proteins (Figure 10A) are split into two main clades, each including one tomato protein. The domain architecture of the first group is characterized by the presence of a kinase C-terminal APH domain (PF01636), which is not observed in the other group.

Phylogenetic analysis of the proteins belonging to this class suggests that they are highly conserved among species. The KDM5 class (Figure 10B) is divided into two main clades, one of which has three tomato proteins, the other only one. The first includes the proteins with the C-terminal FYRN and FYRC domains and the other the BRIGHT/ARID domain proteins [68]. SIJM16 lacks the conserved C-terminal domains (FYRN and FYRC) and SIJM6 has a duplication of the region encoding the PLU-1 (PF08429)-PHD domains. The PLU-1 domain is involved in the DNA-binding domain and it was not described before in JMJ demethylases. The KDM3 phylogenetic tree (Figure 11) has two main clades with a high bootstrap value. Interestingly, five proteins, three of which are found in tomato (SIJM13-15), have an N-terminal WRC domain (PF08879) which includes a putative nuclear localization signal and a zinc-finger motif which was not described previously in this class. A modified RING-finger domain named R1 (PF10497) was also identified in the tomato SIJM17. A tandem duplication of the *SIJM19* gene was observed.

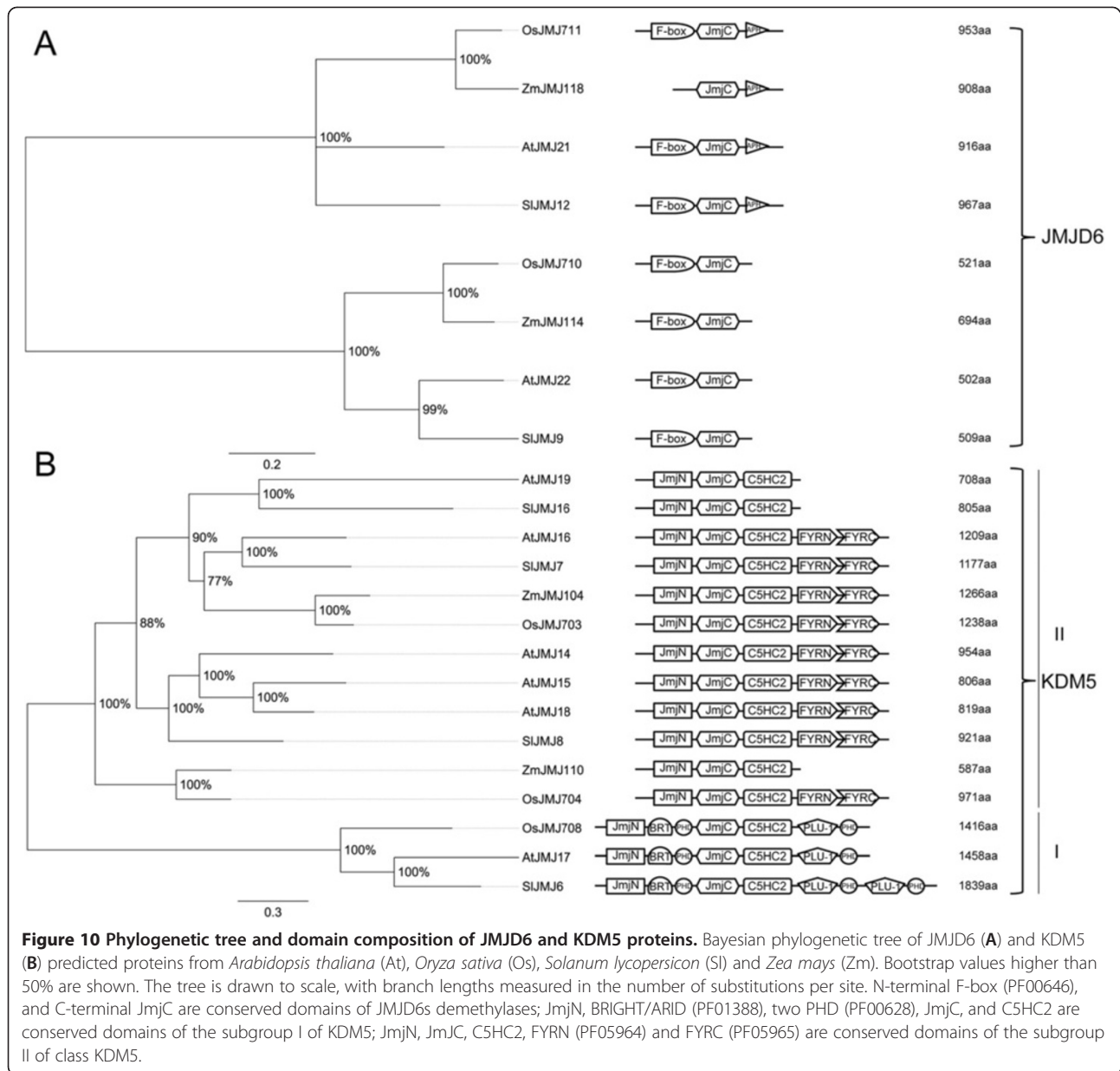
The wide expression profile of tomato *JMJs* (see Additional file 10) in several organs suggests that they could play a global role in plant development. However, some *JMJs* showed specific expression peaks, thereby suggesting particular roles. This is the case of *SIJM17* and *SIJM7* which are preferentially expressed in roots while *SIJM3*, *SIJM8*, *SIJM4* and *SIJM20* in buds and/or flowers, suggesting a role in gamete formation or flower development. Interestingly, SIJM8 is the closest



homolog to AtJMJ14, which is highly expressed in flowers [51] and acts as a repressor of the photoperiodic pathway [69]. *SlJMJ12*, *SlJMJ16*, *SlJMJ5* and *SlJMJ13* are particularly expressed in fruit at B10, thus suggesting a role in later processes of fruit and/or embryo/seed development.

Association of tomato HMs to *S. pennellii* introgression lines (ILs): a case study

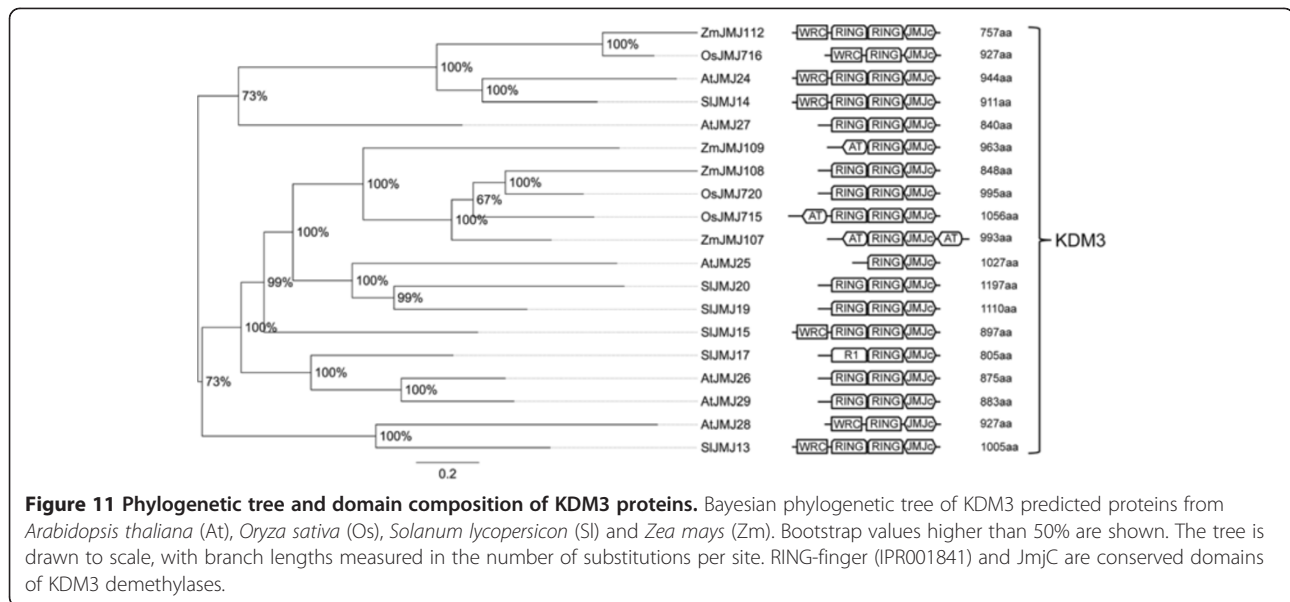
To identify candidate genes involved in epigenetically regulated processes by means of *in silico* analysis we looked for ILs where HMs were associated, based on their map position on the tomato genome (see Additional file 12).



We failed to recover ILs for *SIHAG15*, which is not assigned to any chromosome (chr), and for *SIJM4* (chr4), *SIPRMT6* (chr8), *SISDG5* (chr2), *SISDG35* (chr12), *SISDG43* (chr1) located terminally on different chromosomes outside the available markers. We then combined the information about the phenotype of ILs with *HM* expression profiles described in the previous sections.

As a case study, we report the identification of a candidate HM involved in carotenoid biosynthesis in tomato fruits. It should first be noted that the *Arabidopsis* histone methyltransferase *AtSDG8* is required for the expression of the carotenoid isomerase *AtCRTISO* [51]. The tomato homolog of *AtCRTISO* was characterized by

Isaacson and colleagues [70] as an essential gene for the production of all *trans*-lycopene. As reported above, our analysis highlighted that two homologs of *AtSDG8* occur in tomato, i.e. *SISDG33* and *SISDG34*. It should be pointed out that *SISDG33* is a stronger candidate than *SISDG34* as it is involved in *CRTISO-like* regulation and hence in the carotenoid composition of the tomato fruit. Indeed, similar to what is observed for tomato *CRTISO*, *SISDG33* is upregulated during fruit ripening (see Additional file 13) with a peak of expression in fruit at B and B10. Furthermore, it maps on IL4-3-2 that is reported to have a QTL affecting fruit color, which is known to be dependent on carotenoid biosynthesis [71].



Conclusions

It is well known that a large genome dataset accelerates gene discovery in plants. In this study, we identified *in silico* 124 HMs in tomato including 32 HATs, 14 HDACs, 52 HMTs, and 26 HDMs. The characterization of HM proteins based on domain annotation was very useful for discovering new family members and new families. Indeed, we revised the canonical family annotation of plant HAGs, reporting the existence in plants of HPA2-like proteins, so far described only in fungi. Moreover, we found that HPA2-like proteins represent the largest group of HAGs both in *Arabidopsis* and in tomato. Furthermore, we identified a new HAT family, named GLM, revealing that it occurs in 12 plant species. Phylogenetic analysis allowed us to trace the evolutionary history of plant HMs, evidencing their diversification among dicot and monocot species included in this study. By analyzing the expression data of all the HMs identified in this study, we were able to provide an overview of the putative role of these genes in tomato development. In this way we supplied useful inputs to discover genes with broader as well as more specific roles. Our datasets might help to address several biological questions and explore the relationship between genomes and phenotypes. Indeed, we propose to combine genome-wide knowledge of HMs with the phenotype information of tomato ILs to prioritize candidate genes involved in the process of interest.

Methods

Data collection and prediction of tomato HMs

The protein sequences of histone modifiers (HMs) from *Arabidopsis thaliana*, *Oryza sativa* and *Zea mays* were retrieved from ChromDB (www.chromdb.org) and are listed in Additional file 14. In order to complete the

catalogue of *Arabidopsis* HAGs and of maize JMJs, the TAIR10 (www.arabidopsis.org) and Zmays166 (<http://www.phytozome.net/>) proteome were downloaded and a BLAST [72] search was then performed using as query the catalytic domain Acetyltransf_1 (PF00583) and different members of *Arabidopsis* JMJ subfamilies, respectively. The proteins showing only the Acetyltransf_1 and the JMJC catalytic domain (PF02373) were selected. All proteins retrieved were annotated with InterProScan, and for each family of HM a multiple alignment with MUSCLE [73] was performed. The typical domains of each HM family were extracted from the multiple alignments and used to build specific HMM profiles with HMMER v2.1 [74]. The HMM profiles, after calibration, were used as matrix to search for putative HM proteins in the tomato proteome (FASTA file of all predicted proteins of tomato v2.40).

The homologous proteins to SIHAG4 were found by BLAST search against the proteomes of 29 plant organisms (Phytozome v8.0; www.phytozome.net). The Interpro database was queried to identify all the proteins showing both the HAT1_N (PF10394) and the MOZ_SAS (PF01853) domains. The list of SIHAG4 homologous proteins and that found in Interpro is reported in Additional file 15.

HM domain identification

The domain composition of HMs from *Solanum lycopersicon*, *Arabidopsis thaliana*, *Oryza sativa* and *Zea mays* was inferred with SMART [75] looking for outlier homologs and PFAM domains.

Molecular phylogenetic analysis

Phylogeny history of HMs was inferred within Phylogeny.fr environment (<http://www.phylogeny.fr/version2.cgi/index.cgi>;

[76]) Each HM protein group was aligned with MUSCLE [73]. Bayesian phylogeny reconstruction using MrBayes (substitution model = Blosom62; number of generations = 100000; sampling frequency = 100; burnin = 1000) was performed for HAC, HAF, HAM, HDMA, HDT, JMJ and SRT protein families. Maximum Likelihood phylogeny reconstruction was employed for HAG, HDA, PRMT and SDG protein families with PhyML. The bootstrap consensus tree was inferred from 100 replicates [77]. The phylogenetic trees were visualized with FigTree 1.3.1 (<http://tree.bio.ed.ac.uk/software/figtree/>).

Expression data visualization

The expression data of tomato *HMs* extracted from dataset of the Tomato Genome Consortium [34] were visualized with Matrix2PNG (<http://www.chibi.ubc.ca/matrix2png/bin/matrix2png.cgi>; [78]). The expression data of *JMJ*s, *PRMT*s and *SDG*s were normalized to have mean zero and variance one before producing the heat maps. The genes belonging to each HM family were grouped according to their expression profiles in fruits as calculated with MEV 4.8.1 [79,80] by using the Gene Distance Matrix tool.

Mapping of tomato HM on introgression lines (ILs)

S. pennellii IL bins (IL-bins) [81] were visualized on the Sol Genomics Network website (<http://solgenomics.net>). In order to define the starting and ending point of each IL-bin on the tomato genome, edge molecular marker sequences (MMs) were downloaded. Genome coordinates of MMs were retrieved using BLASTn query against the *Solanum lycopersicon* 2.30 genome (see Additional file 16). The starting coordinate of each tomato *HM* was then compared to coordinates of MMs to establish associations (see Additional file 12).

Additional files

Additional file 1: Phylogenetic tree of AT1-domain containing proteins. Maximum likelihood phylogenetic tree of predicted proteins from *Arabidopsis thaliana* (At) and *Solanum lycopersicon* (Sl) containing an Acetyltrans_1 domain. Bootstrap values higher than 50% are shown. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site. GCN5-like, ELP3-like, HAT1-like and HPA2-like proteins are highlighted in spring green, yellow and green, respectively.

Additional file 2: Phylogenetic tree of GML proteins. Maximum likelihood phylogenetic tree of predicted proteins from 32 organisms. Bootstrap values are shown for each node. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site. Ac = *Aquilegia coerulea*; Al = *Arabidopsis lyrata*; At = *Arabidopsis thaliana*; Bd = *Brachypodium distachyon*; Br = *Brassica rapa*; Car = *Capsella rubella*; Cc = *Citrus clementina*; Cis = *Citrus sinensis*; Cp = *Carica papaya*; Cr = *Chlamydomonas reinhardtii*; Cs = *Cucumis sativus*; Es = *Ectocarpus siliculosus*; Eu = *Eucalyptus grandis*; Gm = *Glycine max*; Lu = *Linum usitatissimum*; Md = *Malus domestica*; Me = *Manihot esculenta*; Mg = *Mimulus guttatus*; Mt = *Medicago truncatula*; Os = *Oryza sativa*; Pp = *Physcomitrella patens*; Pt = *Populus trichocarpa*; Pv = *Phaseolus vulgaris*; Sb = *Sorghum bicolor*; Si = *Setaria italica*; Sl = *Solanum lycopersicon*; Ta = *Trichoplax adhaerens*; Th = *Thellungiella halophila*; Vc = *Volvox carter*; Vv =

Vitis vinifera; Zm = *Zea mays*. The proteins showing both the HAT1_N and the MOZ_SAS domain are highlighted in yellow.

Additional file 3: Phylogenetic tree of HAM proteins. Bayesian phylogenetic tree of HAM predicted proteins from *Arabidopsis thaliana* (At), *Oryza sativa* (Os), *Solanum lycopersicon* (Sl) and *Zea mays* (Zm). Bootstrap values higher than 50% are shown. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site.

Additional file 4: Expression profiles of tomato HDACs. Heat map of RNA-seq expression data from root, leaf, bud, flower, 1cm_fruit, 2cm_fruit, 3cm_fruit, mature green fruit (MG), berry at breaker stage (B) and berry ten days after breaking (B10). HDACs with low, middle and high expression values are reported in A, B and C, respectively. The expression values are measured as reads per kilobase of exon model per million mapped reads (RPKM).

Additional file 5: Phylogenetic tree of SRT proteins. Bayesian phylogenetic tree of SRT predicted proteins from *Arabidopsis thaliana* (At), *Oryza sativa* (Os), *Solanum lycopersicon* (Sl) and *Zea mays* (Zm). Bootstrap values higher than 50% are shown. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site.

Additional file 6: Phylogenetic tree of HDT proteins. Bayesian phylogenetic tree of HDT predicted proteins from *Arabidopsis thaliana* (At), *Oryza sativa* (Os), *Solanum lycopersicon* (Sl) and *Zea mays* (Zm). Bootstrap values higher than 50% are shown. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site.

Additional file 7: Phylogenetic tree of PRMT proteins. Maximum likelihood phylogenetic tree of PRMT predicted proteins from *Arabidopsis thaliana* (At), *Oryza sativa* (Os), *Solanum lycopersicon* (Sl) and *Zea mays* (Zm). Bootstrap values higher than 50% are shown. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site.

Additional file 8: Expression profiles of tomato PRMTs. Heat map RNA-seq expression data from root, leaf, bud, flower, 1cm_fruit, 2cm_fruit, 3cm_fruit, mature green fruit (MG), berry at breaker stage (B) and berry ten days after breaking (B10). The expression values are measured as reads per kilobase of exon model per million mapped reads (RPKM).

Additional file 9: Phylogenetic tree of HDMA proteins. Bayesian phylogenetic tree of HDMA predicted proteins from *Arabidopsis thaliana* (At), *Oryza sativa* (Os), *Solanum lycopersicon* (Sl) and *Zea mays* (Zm). Bootstrap values higher than 50% are shown. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site.

Additional file 10: Expression profiles of tomato HMAs. Heat map of RNA-seq expression data from root, leaf, bud, flower, 1cm_fruit, 2cm_fruit, 3cm_fruit, mature green fruit (MG), berry at breaker stage (B) and berry ten days after breaking (B10). HDMAs with low, middle and high expression values are reported in A, B and C, respectively. The expression values are measured as reads per kilobase of exon model per million mapped reads (RPKM).

Additional file 11: Phylogenetic tree of JMJ proteins. Maximum likelihood phylogenetic tree of JMJ predicted proteins from *Arabidopsis thaliana* (At), *Oryza sativa* (Os), *Solanum lycopersicon* (Sl) and *Zea mays* (Zm). Bootstrap values higher than 50% are shown. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site.

Additional file 12: List of the associations between tomato histone modifier genes and introgression lines (ILs).

Additional file 13: Expression profiles of CRTISO and putative SDGs involved in carotenoid synthesis. Heat map of CRTISO, SISDG33 and SISDG34 RNA-seq expression data from 1cm_fruit, 2cm_fruit, 3cm_fruit, mature green fruit (MG), berry at breaker stage (B) and berry ten days after breaking (B10). The expression values are measured as reads per kilobase of exon model per million mapped reads (RPKM).

Additional file 14: List of the histone modifiers from Arabidopsis thaliana, Oryza sativa and Zea mays used in this study.

Additional file 15: List of the SIHAG4 homologous sequences used to reconstruct GML evolutionary history.

Additional file 16: List of the starting (S) and ending (E) molecular markers, with the corresponding coordinates, used to map tomato ILs.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

RAC performed the data collection and the analysis of protein domains and ILS, participated in phylogenetic and expression analyses, study design and drafted the manuscript. WS performed the phylogenetics and expression profiles, and participated in bioinformatic analysis design. GC assisted in the interpretation of data. MRE provided advisory support in the bioinformatic analysis and revised the manuscript. CC conceived of the study and revised the manuscript. FMC conceived of and coordinated the study, and revised the manuscript. All authors read and approved the final manuscript.

Acknowledgments

The authors wish to thank Prof JJ Giovannoni and Dr Z Fei for helpful advice in bioinformatics. Valuable technical and graphic support was provided by R Paparo and G Guarino, respectively. This work was funded by the Italian Ministry of Education, University and Scientific Research (project GenoPOMpro, PON02_00395_3082360).

Author details

¹CNR, National Research Council of Italy, Institute of Plant Genetics, Research Division Portici, Via Università 133, 80055, Portici, Italy. ²DISSPAPA, Department of Soil, Plant and Environmental Sciences, University of Naples "Federico II", Via Università 100, 80055, Portici, Italy.

Received: 16 July 2012 Accepted: 22 January 2013

Published: 28 January 2013

References

- Fransz P, de Jong H: From nucleosome to chromosome: a dynamic organization of genetic information. *Plant J* 2011, **66**:4–17.
- Kouzarides T: Chromatin modifications and their function. *Cell* 2007, **128**:693–705.
- Weber M, Schübeler D: Genomic patterns of DNA methylation: targets and function of an epigenetic mark. *Curr Opin Cell Biol* 2007, **19**:273–280.
- Sadeh R, Allis CD: Genome-wide "re"-modeling of nucleosome positions. *Cell* 2011, **147**:263–266.
- Fuchs J, Demidov D, Houben A, Schubert I: Chromosomal histone modification patterns – from conservation to diversity. *Trends Plant Sci* 2006, **11**:199–208.
- Pandey R, Müller A, Napoli CA, Selinger DA, Pikaard CS, Richards EJ, Bender J, Mount DW, Jorgensen RA: Analysis of histone acetyltransferase and histone deacetylase families of *Arabidopsis thaliana* suggests functional diversification of chromatin modification among multicellular eukaryotes. *Nucleic Acids Res* 2002, **30**:5036–5055.
- Earley KW, Shook MS, Brower-Toland B, Hicks L, Pikaard CS: In vitro specificities of *Arabidopsis* co-activator histone acetyltransferases: implications for histone hyperacetylation in gene activation. *Plant J* 2007, **52**:615–626.
- Uitley RT, Ikeda K, Grant PA, Côté J, Steger DJ, Eberharter A, John S, Workman JL: Transcriptional activators direct histone acetyltransferase complexes to nucleosomes. *Nature* 1998, **394**:498–502.
- Clayton AL, Hazzalin CA, Mahadevan LC: Enhanced histone acetylation and transcription: a dynamic perspective. *Mol Cell* 2006, **23**:289–296.
- Yang XJ, Seto E: HATs and HDACs: from structure, function and regulation to novel strategies for therapy and prevention. *Oncogene* 2007, **26**:5310–5318.
- Hollender C, Liu Z: Histone deacetylase genes in *Arabidopsis* development. *J Integr Plant Biol* 2008, **50**:875–885.
- Tian L, Fong MP, Wang JJ, Wei NE, Jiang H, Doerge RW, Chen ZJ: Reversible histone acetylation and deacetylation mediate genome-wide, promoter-dependent and locus-specific changes in gene expression during plant development. *Genetics* 2005, **169**:337–345.
- Klose RJ, Zhang Y: Regulation of histone methylation by demethyliminination and demethylation. *Nat Rev Mol Cell Biol* 2007, **8**:307–318.
- Jackson JP, Lindroth AM, Cao X, Jacobsen SE: Control of CpNpG DNA methylation by the KRYPTONITE histone H3 methyltransferase. *Nature* 2002, **416**:556–560.
- Jackson JP, Johnson L, Jasencakova Z, Zhang X, PerezBurgos L, Singh PB, Cheng X, Schubert I, Jenuwein T, Jacobsen SE: Dimethylation of histone H3 lysine 9 is a critical mark for DNA methylation and gene silencing in *Arabidopsis thaliana*. *Chromosoma* 2004, **112**:308–315.
- Naumann K, Fischer A, Hofmann I, Krauss V, Phalke K, Hause G, Aurich AC, Dorn R, Jenuwein T, Reuter G: Pivotal role of AtSUVH2 in heterochromatic histone methylation and gene silencing in *Arabidopsis*. *EMBO J* 2005, **24**:1418–1429.
- Fischer A, Hofmann I, Naumann K, Reuter G: Heterochromatin proteins and the control of heterochromatic gene silencing in *Arabidopsis*. *J Plant Physiol* 2006, **163**:358–368.
- Ebbs ML, Bender J: Locus-specific control of DNA methylation by the *Arabidopsis* SUVH5 histone methyltransferase. *Plant Cell* 2006, **18**:1166–1176.
- Hennig L, Derkacheva M: Diversity of Polycomb group complexes in plants: same rules, different players? *Trends Genet* 2009, **25**:414–423.
- Berr A, Shafiq S, Shen WH: Histone modifications in transcriptional activation during plant development. *Biochim Biophys Acta* 2011, **1809**:567–576.
- Liu C, Lu F, Cui X, Cao X: Histone methylation in higher plants. *Annu Rev Plant Biol* 2010, **61**:395–420.
- Thorstensen T, Grini PE, Aalen RB: SET domain proteins in plant development. *Biochim Biophys Acta* 2011, **1809**:407–420.
- Kooistra SM, Helin K: Molecular mechanisms and potential functions of histone demethylases. *Nat Rev Mol Cell Biol* 2012, **13**:297–311.
- Jiang D, Yang W, He Y, Amasino RM: Arabidopsis relatives of the human lysine-specific Demethylase1 repress the expression of FWA and FLOWERING LOCUS C and thus promote the floral transition. *Plant Cell* 2007, **19**:2975–2987.
- Chen X, Hu Y, Zhou DX: Epigenetic gene regulation by plant Jumonji group of histone demethylase. *Biochim Biophys Acta* 2011, **1809**:421–426.
- Lu F, Cui X, Zhang S, Jenuwein T, Cao X: Arabidopsis REF6 is a histone H3 lysine 27 demethylase. *Nat Genet* 2011, **43**:715–719.
- Shi Y, Lan F, Matson C, Mulligan P, Whetstone JR, Cole PA, Casero RA, Shi Y: Histone demethylation mediated by the nuclear amine oxidase homolog LSD1. *Cell* 2004, **119**:941–953.
- Jeong JH, Song HR, Ko JH, Jeong YM, Kwon YE, Seol JH, Amasino RM, Noh B, Noh YS: Repression of FLOWERING LOCUS T chromatin by functionally redundant histone H3 lysine 4 demethylases in *Arabidopsis*. *PLoS One* 2009, **4**:e8033.
- Lu F, Cui X, Zhang S, Liu C, Cao X: JM14 is an H3K4 demethylase regulating flowering time in *Arabidopsis*. *Cell Res* 2010, **20**:387–390.
- Chang B, Chen Y, Zhao Y, Bruick RK: JMJD6 is a histone arginine demethylase. *Science* 2007, **318**:444–447.
- Pagnussat GC, Yu HJ, Ngo QA, Rajani S, Mayalagu S, Johnson CS, Capron A, Xie LF, Ye D, Sundaresan V: Genetic and molecular identification of genes required for female gametophyte development and function in *Arabidopsis*. *Development* 2005, **132**:603–614.
- Jones MA, Harmer S: JMJD5 functions in concert with TOC1 in the *Arabidopsis* circadian system. *Plant Signal Behav* 2011, **6**:445–448.
- Lu SX, Tobin EM: Chromatin remodeling and the circadian clock: Jumonji C-domain containing proteins. *Plant Signal Behav* 2011, **6**:810–814.
- Tomato Genome Consortium: The tomato genome sequence provides insights into fleshy fruit evolution. *Nature* 2012, **485**:635–641.
- Latrasse D, Benhamed M, Henry Y, Domenichini S, Kim W, Zhou DX, Delarue M: The MYST histone acetyltransferases are essential for gametophyte development in *Arabidopsis*. *BMC Plant Biol* 2008, **8**:12.
- Kalamaki MS, Alexandrou D, Lazari D, Merkouropoulos G, Fotopoulos V, Pateraki I, Aggelis A, Carrillo-López A, Rubio-Cabetas MJ, Kanellis AK: Over-expression of a tomato N-acetyl-L-glutamate synthase gene (SINAGS1) in *Arabidopsis thaliana* results in high ornithine levels and increased tolerance in salt and drought stresses. *J Exp Bot* 2009, **60**:1859–1871.
- Perrella G, Consiglio MF, Aiese-Cigliano R, Cremona G, Sanchez-Moran E, Barra L, Errico A, Bressan RA, Franklin FCH, Conicella C: Histone hyperacetylation affects meiotic recombination and chromosome segregation in *Arabidopsis*. *Plant J* 2010, **62**:796–806.
- Servet C, Conde E, Silva N, Zhou DX: Histone acetyltransferase AtGCN5/HAG1 is a versatile regulator of developmental and inducible gene expression in *Arabidopsis*. *Mol Plant* 2010, **3**:670–677.
- Nelissen H, Fleury D, Bruno L, Robles P, De Veylder L, Traas J, Micol JL, Van Montagu M, Inzé D, Van Lijsebettens M: The elongata mutants identify a

- functional Elongator complex in plants with a role in cell proliferation during organ growth. *Proc Natl Acad Sci USA* 2005, **102**:7754–7759.
40. Nelissen H, De Groeve S, Fleury D, Neyt P, Bruno L, Bitonti MB, Vandenbussche F, Van der Straeten D, Yamaguchi T, Tsukaya H, Witters E, De Jaeger G, Houben A, Van Lijsebettens M: **Plant Elongator regulates auxin-related genes during RNA polymerase II transcription elongation.** *Proc Natl Acad Sci USA* 2010, **107**:1678–1683.
 41. Kojima S, Iwasaki M, Takahashi H, Imai T, Matsumura Y, Fleury D, Van Lijsebettens M, Machida Y, Machida C: **Asymmetric leaves2 and Elongator, a histone acetyltransferase complex, mediate the establishment of polarity in leaves of Arabidopsis thaliana.** *Plant Cell Physiol* 2011, **52**:1259–1273.
 42. Han SK, Song JD, Noh YS, Noh B: **Role of plant CBP/p300-like genes in the regulation of flowering time.** *Plant J* 2007, **49**:103–114.
 43. Deng W, Liu C, Pei Y, Deng X, Niu L, Cao X: **Involvement of the histone acetyltransferase AtHAC1 in the regulation of flowering time via repression of FLOWERING LOCUS C in Arabidopsis.** *Plant Physiol* 2007, **143**:1660–1668.
 44. Alisung MV, Yu CW, Wu K: **Phylogenetic analysis, subcellular localization, and expression patterns of RPD3/HDAl family histone deacetylases in plants.** *BMC Plant Biol* 2009, **9**:37.
 45. Xu CR, Liu C, Wang YL, Li LC, Chen WQ, Xu ZH, Bai SN: **Histone acetylation affects expression of cellular patterning genes in the Arabidopsis root epidermis.** *Proc Natl Acad Sci USA* 2005, **102**:14469–14474.
 46. Tanaka M, Kikuchi A, Kamada H: **The Arabidopsis histone deacetylases HDA6 and HDA19 contribute to the repression of embryonic properties after germination.** *Plant Physiol* 2008, **146**:149–161.
 47. Long JA, Ohno C, Smith ZR, Meyerowitz EM: **TOPLLESS regulates apical embryonic fate in Arabidopsis.** *Science* 2006, **312**:1520–1523.
 48. Bond DM, Dennis ES, Pogson BJ, Finnegan EJ: **Histone acetylation, VERNALIZATION INSENSITIVE 3, FLOWERING LOCUS C, and the vernalization response.** *Mol Plant* 2009, **2**:724–737.
 49. Springer NM, Napoli CA, Selinger DA, Pandey R, Cone KC, Chandler VL, Kaeppler HF, Kaeppler SM: **Comparative analysis of SET domain proteins in maize and Arabidopsis reveals multiple duplications preceding the divergence of monocots and dicots.** *Plant Physiol* 2003, **132**:907–925.
 50. Sadder M, Alsadon A, Al-Thamra M, Zakri A, Al-Doss A: **Phylogenetic Analysis of SET Domain in Trithorax SITX1 of Solanum lycopersicum.** *Plant Omics* 2011, **4**:95.
 51. Schmid M, Davison TS, Henz SR, Pape UJ, Demar M, Vingron M, Schölkopf B, Weigel D, Lohmann JU: **A gene expression map of Arabidopsis thaliana development.** *Nature Genet* 2005, **37**:501–506.
 52. Cazzonelli CI, Cuttriss AJ, Cossetto SB, Pye W, Crisp P, Whelan J, Finnegan EJ, Turnbull C, Pogson BJ: **Regulation of carotenoid composition and shoot branching in Arabidopsis by a chromatin modifying histone methyltransferase, SDG8.** *Plant Cell* 2009, **21**:39–53.
 53. Cartagena JA, Matsunaga S, Seki M, Kurihara D, Yokoyama M, Shinozaki K, Fujimoto S, Azumi Y, Uchiyama S, Fukui K: **The Arabidopsis SDG4 contributes to the regulation of pollen tube growth by methylation of histone H3 lysines 4 and 36 in mature pollen.** *Dev Biol* 2008, **315**:355–368.
 54. Berr A, McCallum EJ, Ménard R, Meyer D, Fuchs J, Dong A, Shen WH: **Arabidopsis SET DOMAIN GROUP2 is required for H3K4 trimethylation and is crucial for both sporophyte and gametophyte development.** *Plant Cell* 2010, **22**:3232–3248.
 55. Guo L, Yu Y, Law JA, Zhang X: **SET DOMAIN GROUP2 is the major histone H3 lysine 4 trimethyltransferase in Arabidopsis.** *Proc Natl Acad Sci USA* 2010, **107**:18557–18562.
 56. Ndamukong I, Chetram A, Saleh A, Avramova Z: **Wall-modifying genes regulated by the Arabidopsis homolog of trithorax, ATX1: repression of the XTH33 gene as a test case.** *Plant J* 2009, **58**:541–553.
 57. Arowsmith DA, de Silva J: **Characterisation of two tomato fruit-expressed cDNAs encoding xyloglucan endo-transglycosylase.** *Plant Mol Biol* 1995, **28**:391–403.
 58. Berr A, Xu L, Gao J, Cognat V, Steinmetz A, Dong A, Shen WH: **SET DOMAIN GROUP25 encodes a histone methyltransferase and is involved in FLOWERING LOCUS C activation and repression of flowering.** *Plant Physiol* 2009, **151**:1476–1485.
 59. Krause CD, Yang ZH, Kim YS, Lee JH, Cook JR, Pestka S: **Protein arginine methyltransferases: evolution and assessment of their pharmacological and therapeutic potential.** *Pharmacol Ther* 2007, **113**:50–87.
 60. Yan D, Zhang Y, Niu L, Yuan Y, Cao X: **Identification and characterization of two closely related histone H4 arginine 3 methyltransferases in Arabidopsis thaliana.** *Biochem J* 2007, **408**:113–121.
 61. Sceba F, De Bastiani M, Bernacchia G, Andreucci A, Galli A, Pitto L: **PRMT11: a new Arabidopsis MBD7 protein partner with arginine methyltransferase activity.** *Plant J* 2007, **52**:210–222.
 62. Niu L, Lu F, Pei Y, Liu C, Cao X: **Regulation of flowering time by the protein arginine methyltransferase AtPRMT10.** *EMBO Rep* 2007, **8**:1190–1195.
 63. Niu L, Zhang Y, Pei Y, Liu C, Cao X: **Redundant requirement for a pair of PROTEIN ARGININE METHYLTRANSFERASE4 homologs for the proper regulation of Arabidopsis flowering time.** *Plant Physiol* 2008, **148**:490–503.
 64. Pei Y, Niu L, Lu F, Liu C, Zhai J, Kong X, Cao X: **Mutations in the Type II protein arginine methyltransferase AtPRMT5 result in pleiotropic developmental defects in Arabidopsis.** *Plant Physiol* 2007, **144**:1913–1923.
 65. Zhang Z, Zhang S, Zhang Y, Wang X, Li D, Li Q, Yue M, Li Q, Zhang YE, Xu Y, Xue Y, Chong K, Bao S: **Arabidopsis floral initiator SKB1 confers high salt tolerance by regulating transcription and pre-mRNA splicing through altering histone H4R3 and small nuclear ribonucleoprotein LSM4 methylation.** *Plant Cell* 2011, **23**:396–411.
 66. Krichevsky A, Gutgarts H, Kozlovsky SV, Sutton A, Sternglanz R, Mandel G, Citovsky V: **C2H2 zinc finger-SET histone methyltransferase is a plant-specific chromatin modifier.** *Dev Biol* 2007, **303**:259–269.
 67. Krichevsky A, Zaltsman A, Kozlovsky SV, Tian GW, Citovsky V: **Regulation of Root Elongation by Histone Acetylation in Arabidopsis.** *J Mol Biol* 2009, **385**:45–50.
 68. Lu F, Li G, Cui X, Liu C, Wang XJ, Cao X: **Comparative analysis of JmjC domain-containing proteins reveals the potential histone demethylases in Arabidopsis and rice.** *J Integr Plant Biol* 2008, **50**:886–896.
 69. Noh B, Lee SH, Kim HJ, Yi G, Shin EA, Lee M, Jung KJ, Doyle MR, Amasino RM, Noh YS: **Divergent roles of a pair of homologous jumonji/zinc-finger-class transcription factor proteins in the regulation of Arabidopsis flowering time.** *Plant Cell* 2004, **16**:2601–2613.
 70. Isaacson T, Ohad I, Beyer P, Hirschberg J: **Analysis in vitro of the enzyme CRTISO establishes a poly-cis-carotenoid biosynthesis pathway in plants.** *Plant Physiol* 2004, **136**:4246–4255.
 71. Liu YS, Gur A, Ronen G, Causse M, Damidaux R, Buret M, Hirschberg J, Zamir D: **There is more to tomato fruit colour than candidate carotenoid genes.** *Plant Biotechnol J* 2003, **1**:195–207.
 72. Altschul SF, Gish W, Miller W, Myers EW, Lipman DJ: **Basic local alignment search tool.** *J Mol Biol* 1990, **215**:403–410.
 73. Edgar RC: **MUSCLE: a multiple sequence alignment method with reduced time and space complexity.** *BMC Bioinformatics* 2004, **5**:113.
 74. Finn RD, Clements J, Eddy SR: **HMMER web server: interactive sequence similarity searching.** *Nucleic Acids Res* 2011, **39**:W29–W37.
 75. Schultz J, Milpetz F, Bork P, Ponting CP: **SMART, a simple modular architecture research tool: identification of signaling domains.** *Proc Natl Acad Sci USA* 1998, **95**:5857–5864.
 76. Dereeper A, Guignon V, Blanc G, Audic S, Buffet S, Chevenet F, Dufayard JF, Guindon S, Lefort V, Lescot M, Claverie JM, Gascuel O: **Phylogeny fr: robust phylogenetic analysis for the non-specialist.** *Nucleic Acids Res* 2008, **36**:W465–W469.
 77. Felsenstein J: **Confidence limits on phylogenies: an approach using the bootstrap.** *Evolution* 1985, **39**:783–791.
 78. Pavlidis P, Noble WS: **Matrix2png: a utility for visualizing matrix data.** *Bioinformatics* 2003, **19**:295–296.
 79. Saeed AI, Sharov V, White J, Li J, Liang W, Bhagabati N, Braisted J, Klapa M, Currier T, Thiagarajan M, Sturn A, Snuffin M, Rezantsev A, Popov D, Ryltsov A, Kostukovich E, Borisovsky I, Liu Z, Vinsavich A, Trush V, Quackenbush J: **TM4: a free, open-source system for microarray data management and analysis.** *Biotechniques* 2003, **34**:374–378.
 80. Saeed AI, Bhagabati NK, Braisted JC, Liang W, Sharov V, Howe EA, Li J, Thiagarajan M, White JA, Quackenbush J: **TM4 microarray software suite.** *Methods Enzymol* 2006, **411**:134–193.
 81. Eshed Y, Zamir D: **A genomic library of Lycopersicon pennellii in L. esculentum: a tool for fine mapping of genes.** *Euphytica* 1994, **79**:175–179.

doi:10.1186/1471-2164-14-57

Cite this article as: Aiese Cigliano et al.: Genome-wide analysis of histone modifiers in tomato: gaining an insight into their developmental roles. *BMC Genomics* 2013 **14**:57.