

Expansion and Diversification of the *Populus* R2R3-MYB Family of Transcription Factors^{1[W][OA]}

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The R2R3-MYB proteins comprise one of the largest families of transcription factors in plants. R2R3-MYB family members regulate plant-specific processes, such as the elaboration of specialized cell types, including xylem, guard cells, trichomes, and root hairs, and the biosynthesis of specialized branches of metabolism, including phenylpropanoid biosynthesis. As such, R2R3-MYB family members are hypothesized to contribute to the emergence of evolutionary innovations that have arisen in specific plant lineages. As a first step in determining the role played by R2R3-MYB family members in the emergence of lineage-specific innovations in the genus *Populus*, the entire *Populus trichocarpa* R2R3-MYB family was characterized. The *Populus* R2R3-MYB complement is much larger than that found in other angiosperms with fully sequenced genomes. Phylogenetic analyses, together with chromosome placement, showed that the expansion of the *Populus* R2R3-MYB family was not only attributable to whole genome duplication but also involved selective expansion of specific R2R3-MYB clades. Expansion of the *Populus* R2R3-MYB family prominently involved members with expression patterns that suggested a role in specific components of *Populus* life history, including wood formation and reproductive development. An expandable compendium of microarray-based expression data (PopGenExpress) and associated Web-based tools were developed to better enable within- and between-species comparisons of *Populus* R2R3-MYB gene expression. This resource, which includes intuitive graphic visualization of gene expression data across multiple tissues, organs, and treatments, is freely available to, and expandable by, scientists wishing to better understand the genome biology of *Populus*, an ecologically dominant and economically important forest tree genus.

Plant growth and development are regulated by the coordinated expression of tens of thousands of genes. This is achieved through the actions of transcription factors, proteins that show sequence-specific DNA binding that activate or repress transcription in response to endogenous and exogenous stimuli (Riechmann et al., 2000). To accommodate the demands of a sessile life form, plants have evolved large families of transcription factors (Riechmann et al., 2000). In the *Arabidopsis* (*Arabidopsis thaliana*) genome, approximately 6% of the estimated total number of genes are transcription factors, of which an estimated 9% encode members of the MYB family (Riechmann et al., 2000).

The MYB gene family is at least one billion years old and is represented in genomes in all major eukaryotic lineages (Lipsick, 1996; Rosinski and Atchley, 1998; Kranz et al., 2000). The MYB proteins are named for the v-MYB oncogene, a determinant of avian myeloblastosis that was first discovered in chickens (Lipsick, 1996). MYB proteins are identified on the basis of a highly conserved N-terminal DNA-binding domain (DBD; Lipsick, 1996). The MYB DBD consists of imperfect repeats of an approximately 50-amino acid region, with each of the repeats giving rise to a helix-helix-loop-helix secondary structure that binds to the major groove of the target DNA sequences (Lipsick, 1996; Stracke et al., 2001). The MYB DBD contains several highly conserved Trp residues, which play a role in sequence-specific binding of DNA (Ogata et al., 1995). In contrast, the region C terminal to the DBD is the activation domain and varies considerably between MYB proteins (Kranz et al., 1998; Jin and Martin, 1999; Stracke et al., 2001; Jiang et al., 2004). This speaks to the wide range of regulatory roles played by members of this family (Kranz et al., 1998; Jin and Martin, 1999; Meissner et al., 1999).

All known animal MYB DBDs consist of three tandem repeats of the MYB motif (designated R1, R2, and R3) and are referred to as 3R-MYB proteins (Rosinski and Atchley, 1998). Plant MYBs may contain three MYB repeats, but more commonly they have only two (R2R3) or one (R1) MYB DBD (Kranz et al., 1998, 2000; Chen et al., 2006). Furthermore, the MYB

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family is greatly expanded in plant genomes relative to animal genomes (Stracke et al., 2001). In all known vertebrate genomes, there are three different 3R-MYB proteins: c-MYB, A-MYB, and B-MYB (Lipsick, 1996; Rosinski and Atchley, 1998). In contrast, in the Arabidopsis genome, there are five 3R-MYB genes and 126 R2R3-MYB genes (Stracke et al., 2001; Durberry et al., 2005), while in rice (*Oryza sativa*), there are 84 R2R3-MYB genes (Jiang et al., 2004).

This expansion of the R2R3-MYB family in plants supports the observation that many R2R3-MYB transcription factors play roles in plant-specific processes. For example, the elaboration of specific epidermal cell types, including trichomes (Oppenheimer et al., 1991; Higginson et al., 2003), root hairs (Wada et al., 1997; Tominaga et al., 2007), and petal epidermis (Perez-Rodriguez et al., 2005; Baumann et al., 2007), is contingent on the activity of R2R3-MYB transcription factors. R2R3-MYB family members also play central roles in the control of plant metabolism, notably regulation of the synthesis of specific classes of phenylpropanoids, such as flavonoids (Mehrtens et al., 2005; Stracke et al., 2007), anthocyanin (Teng et al., 2005; Deluc et al., 2006), and lignins (Patzlaff et al., 2003; Goicoechea et al., 2005; Bedon et al., 2007). R2R3-MYB family members have demonstrated roles in regulating plant responses to phytohormonal cues, including abscisic acid (Abe et al., 1997, 2003) and gibberellin (Gocal et al., 2001), and to environmental signals, such as light (Jin et al., 2000; Hartmann et al., 2005) and water availability (Urao et al., 1996; Jung et al., 2008).

Given the multiplicity of plant-specific processes controlled by R2R3-MYB transcription factors, it has been postulated that the elaboration of the R2R3-MYB family may account for some of the evolutionary innovations that contribute to plant diversity (Riechmann et al., 2000). In Arabidopsis, members of the R2R3-MYB family of transcription factors have been identified, and their targets and expression patterns are being characterized (Kranz et al., 1998; Meissner et al., 1999; Stracke et al., 2001). However, Arabidopsis is an herbaceous, annual plant that is not representative of a large number of important plant species, particularly long-lived woody perennial plants, like forest trees. Trees are distinct from herbaceous species in many ways: they have a self-supporting structure, the secondary growth or wood, and they have a much longer lifespan (Bradshaw et al., 2000; Brunner et al., 2004). The regulatory networks and molecular mechanisms that underlie these unique properties cannot be investigated through the examination of nontree species, thus demonstrating the importance and opportunity presented by the recent publication of the complete genome sequences for two wood-forming species: *Populus trichocarpa* (Tuskan et al., 2006) and *Vitis vinifera* (Velasco et al., 2007).

Molecular evidence suggests that *P. trichocarpa* and Arabidopsis shared their last common ancestor some 100 to 120 million years ago (Tuskan et al., 2006). Since then, Arabidopsis and *P. trichocarpa* have evolved

different life histories, including herbaceous versus arboreal development, annual versus perennial habit, and selfing versus outcrossing mating strategies. In both plants and animals, the evolution of such diversity has been hypothesized to be the consequence of changes in the expression pattern of the genes encoding transcription factors and/or changes in the functions of the transcription factors themselves (Doebley and Lukens, 1998; Weatherbee et al., 1998). The elaboration of the R2R3-MYB transcription factor family is postulated to account for some of the evolutionary innovations that contribute to plant diversity (Jin and Martin, 1999). Here, we explore the contribution of R2R3-MYB proteins in the diversification of plant form and function through an analysis of the entire R2R3-MYB family encoded in the *Populus* genome.

RESULTS AND DISCUSSION

The *Populus* R2R3-MYB Family Is Larger Than That of Other Sequenced Dicotyledonous Angiosperms

The *Populus* R2R3-MYB family was compared with the corresponding families from the woody perennial *Vitis vinifera*, which is a sister taxon to *Populus* in Eurosids I, and the more distantly related Arabidopsis, which is a member of Eurosids II. The predicted R2 and R3 MYB repeats of the MYB DBD are highly conserved across plant lineages (Jin and Martin, 1999). Using the conserved N-terminal DBD as the defining feature, 192 genes in the *P. trichocarpa* genome were annotated as encoding R2R3-MYB proteins and five genes were annotated as encoding 3R-MYB proteins (Table I; Supplemental Table S1). Like their counterparts in other plant species, the R2 and R3 MYB repeats of the *P. trichocarpa* R2R3-MYB family contain characteristic amino acids, including a series of evenly distributed and highly conserved Trp residues that play a role in sequence-specific binding of DNA (Ogata et al., 1995; Stracke et al., 2001; Fig. 1). In keeping with this, the phylogeny constructed with all predicted *Populus* 3R-MYB and R2R3-MYB proteins, plus all Arabidopsis and *V. vinifera* family members (Fig. 2), is highly similar to a previously published phylogeny that included all known Arabidopsis and rice R2R3-MYB proteins (Jiang et al., 2004). Most of the subgroups described in this previously published phylogeny, defined on the basis of their Arabidopsis complement, are maintained in the current phylogeny, with most subgroups merely expanding to include

Table I. R2R3- and 3R-MYB gene complements of Arabidopsis, *V. vinifera*, and *P. trichocarpa*

Organism	R2R3-MYB	3R-MYB
Arabidopsis	126	5
<i>V. vinifera</i>	118	5
<i>P. trichocarpa</i>	192	5

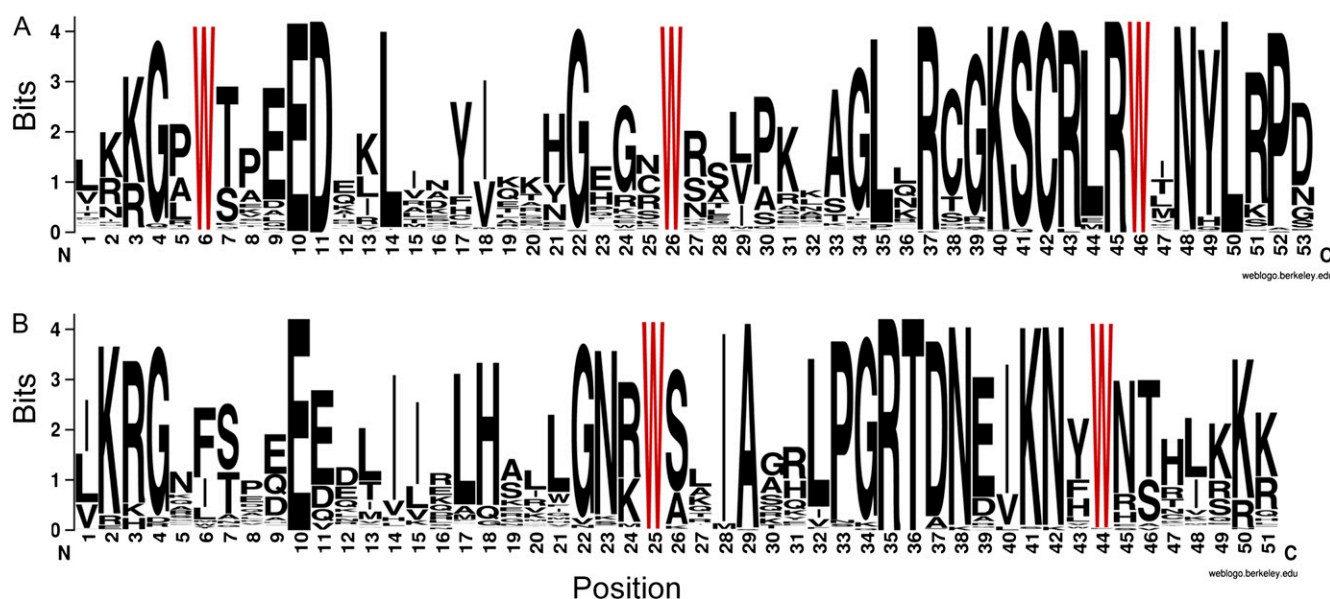


Figure 1. The R2 and R3 MYB repeats are highly conserved across all R2R3-MYB proteins in the *P. trichocarpa* genome. The sequence logos of the R2 (A) and R3 (B) MYB repeats are based on full-length alignments of all PtrR2R3-MYB proteins. The bit score indicates the information content for each position in the sequence. Highly conserved Trp residues required for DNA binding are highlighted in red. PtrMYB proteins in clade 27 have an additional four amino acids directly before the first conserved Trp in R3 (Supplemental Fig. S2A).

both *Populus* and *Vitis* R2R3-MYB members (Supplemental Table S2).

The *P. trichocarpa* genome encodes many more R2R3-MYB family members (192) than either *Arabidopsis* (126; Stracke et al., 2001; Durberry et al., 2005) or *V. vinifera* (123). This expansion appears to be the result of multiple gene duplication processes, including a whole-genome duplication event in the *Populus* lineage as well as multiple segmental and tandem duplication events (Tuskan et al., 2006). To examine the relative contribution of each of these factors in the expansion of the R2R3-MYB family, R2R3-MYB genes were electronically mapped to loci across all 19 linkage groups (LG). In total, 172 *Populus* R2R3-MYB genes were mapped; it was not possible to map the remaining 21 R2R3-MYB genes, as they have not yet been assigned to any LG. There are as many as 21 (LG_II) and as few as a single (LG_XVI) R2R3-MYB genes per LG. On average, there is one R2R3-MYB gene every 2.4 Mb.

Expansion of the *Populus* R2R3-MYB Family Has Occurred through Multiple Mechanisms and Resulted in Lineage-Specific Differences in R2R3-MYB Clades

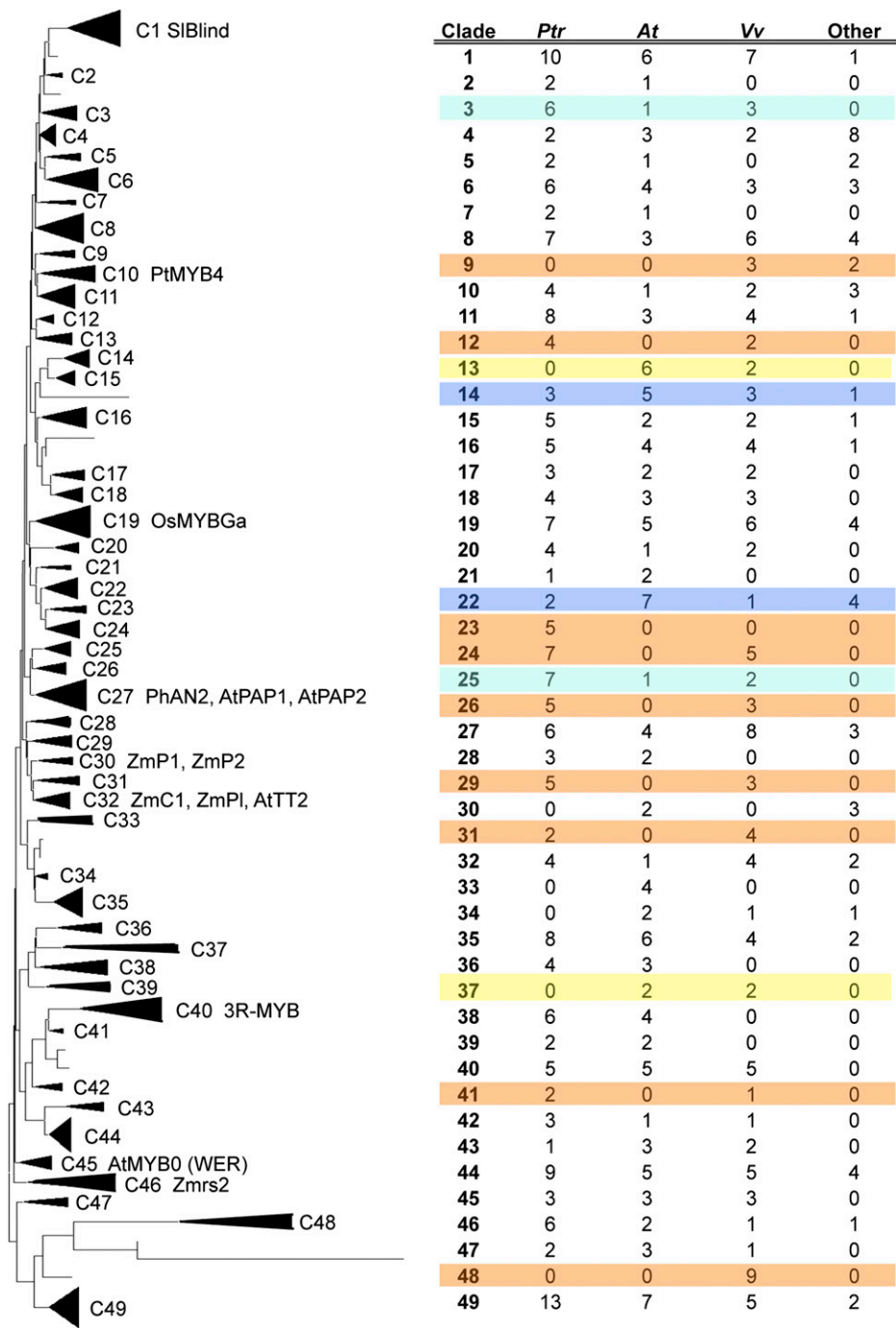
Evidence of the salicoid-specific whole genome duplication event in the *Populus* lineage (approximately 65 million years ago) is present throughout the *P. trichocarpa* genome (Tuskan et al., 2006). Consistent with this, many predicted MYB-encoding genes have paralogous counterparts in syntenic regions of related LGs. For example, large sections of LG_II and LG_V are thought to be the product of the salicoid-specific

genome duplication (Tuskan et al., 2006). In keeping with this, three predicted MYB genes on LG_II (*PtrMYB109*, *PtrMYB189*, and *PtrMYB220*) show conserved organization with three highly similar MYB genes on LG_V (*PtrMYB030*, *PtrMYB158*, and *PtrMYB190*). Many similar examples exist throughout the *Populus* MYB gene family (Fig. 3); however, whole genome duplication can only explain some of the R2R3-MYB gene family expansion observed.

Tandem gene duplication has also played an important role in the elaboration of the R2R3-MYB gene family. More than 35% (68 of 192) of the R2R3-MYB-encoding genes in the *P. trichocarpa* genome are present as tandem repeats, where the gene duplications were directly adjacent to each other on a given LG, with no intervening annotated gene. Tandem repeats most commonly include duplicate or triplicate R2R3-MYB-encoding genes, but there is one instance of four tandem repeats (LG_XI) and one of six repeats (LG_II).

While the number of R2R3-MYB-encoding genes has expanded in *Populus*, the number of 3R-MYB genes has not. That is, *Arabidopsis* (Stracke et al., 2001), *V. vinifera*, and *P. trichocarpa* genomes all encode only five 3R-MYB proteins, despite the fact that they encode a widely varying number of R2R3-MYB proteins: 125, 123, and 192, respectively (Supplemental Tables S1, S3, and S4). The 3R-MYB gene typifies the vertebrate MYB family (Lipsick, 1996) and is present in all major plant lineages (Kranz et al., 2000; Ito, 2005; Haga et al., 2007), suggesting that 3R-MYB genes represent an ancient and evolutionarily conserved gene family. In both plants and vertebrates, 3R-MYB proteins regulate progress through cell cycle transition (Ito et al., 2001; Okada

Figure 2. Phylogenetic relationships and subgroup designations in MYB proteins from *P. trichocarpa* (*Ptr*), *V. vinifera* (*Vv*), and *Arabidopsis* (*At*). The neighbor-joining tree includes 192 R2R3-MYB proteins from *Populus*, 118 from *Vitis*, 126 from *Arabidopsis*, and a further 54 from other plant species, in addition to five 3R-MYB proteins from each of *Populus*, *Vitis*, and *Arabidopsis*. The proteins are clustered into 49 subgroups (triangles), designated with a subgroup number (e.g. C1). Eleven proteins did not fit well into clusters (lines). Some landmark R2R3-MYB proteins are listed to the right of the clades for reference. The membership of each subgroup is described in the table at right. Several clades are highlighted that exemplify lineage-specific R2R3-MYB gene expansion. C3 and C25 (green) show dramatic expansion in the *P. trichocarpa* lineage. C13 and C37 (yellow) do not include any *Ptr*MYB proteins. C14 and C22 (blue) show limited expansion in the *P. trichocarpa* lineage. Many clades do not include any *Arabidopsis* R2R3-MYB proteins (orange). The uncompressed tree with full taxa names is available as Supplemental Figure S1.



et al., 2002; Ito, 2005; Haga et al., 2007). Although there appears to be partially redundant function within this family of genes in *Arabidopsis*, loss-of-function mutations in 3R-MYB genes have been demonstrated to lead to incomplete cytokinesis (Haga et al., 2007). This suggests that 3R-MYB proteins fulfill a number of core cellular functions that are conserved across evolution, while the larger, more diverse family of R2R3-MYB proteins in plants suggests that they may play a role in generating phenotypic diversity within this kingdom.

Phylogenetic analysis of the predicted R2R3-MYB protein sequences revealed that there was not equal representation of *Populus*, *Vitis*, and *Arabidopsis* R2R3-MYB proteins within given clades (Fig. 2; Supplemental Fig. S1). For example, phylogeny subgroup C25, which includes only one *Arabidopsis* MYB protein and two *Vitis* MYB proteins, includes seven *Populus* R2R3-MYB proteins. By contrast, the C13 subgroup includes six *Arabidopsis* and two *Vitis* MYB proteins but not one predicted *Populus* MYB protein. In other cases, such as subgroup C22, there are

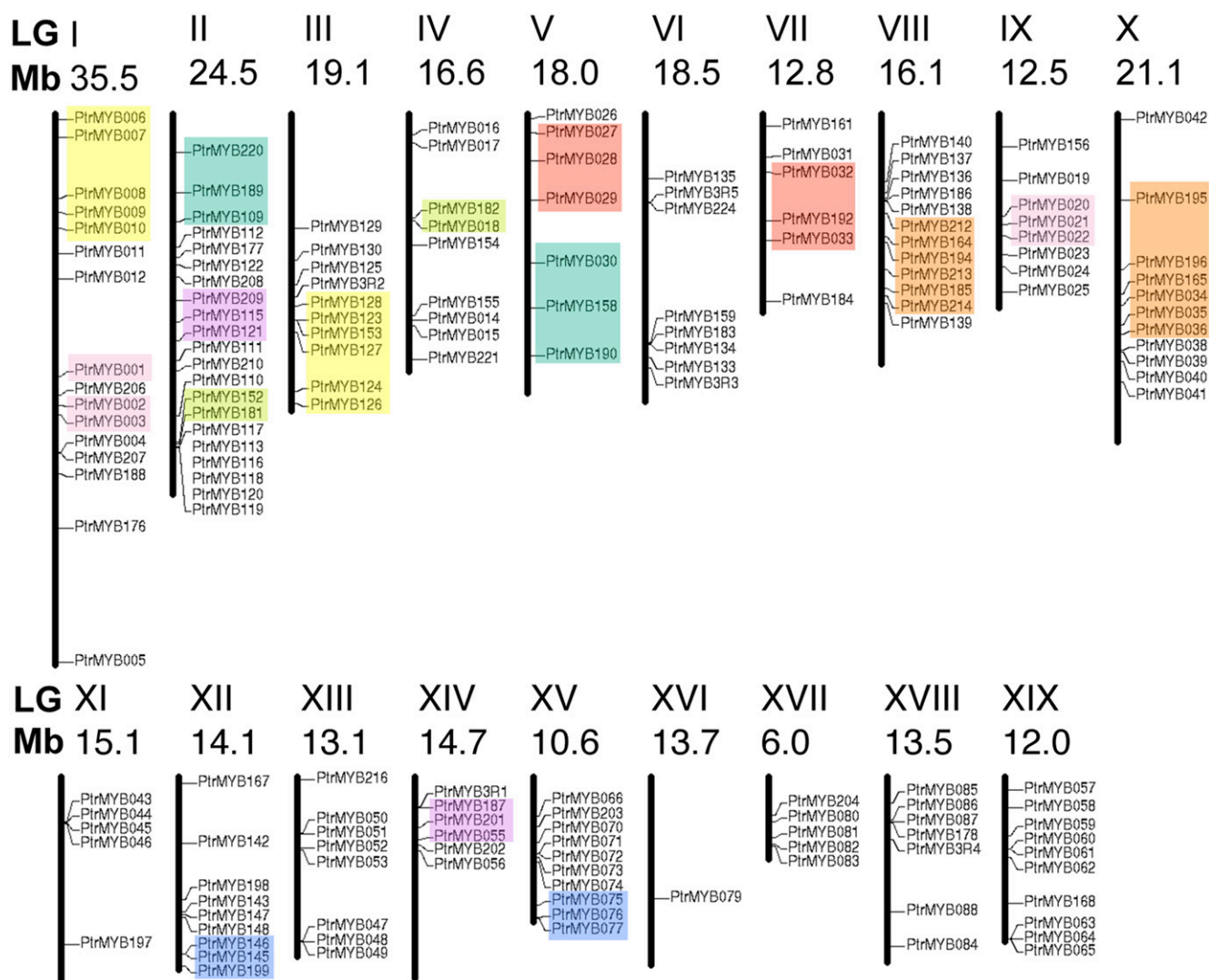


Figure 3. R2R3-MYB and 3R-MYB proteins are present on all LG in the *P. trichocarpa* genome. One hundred seventy-two of the *Populus* R2R3-MYB genes are mapped to LG according to Joint Genome Institute Poplar Genome version 1.1. Each vertical bar represents one LG drawn to scale. The identities of the MYB genes are indicated to the right of the LG on which they are located, with horizontal lines intersecting with the LG indicating their positions. In cases in which multiple MYB genes are located in close proximity on a LG, lines connecting individual gene names and the LG have been omitted. In these cases, angled lines have been used to bracket the relevant gene names and to display their genomic locations. The colored boxes indicate groups of MYB proteins with paralogous and syntenic genes on two LG. The groups indicated are not exhaustive but serve to indicate the widespread evidence of the salicoid-specific whole genome duplication event in the *P. trichocarpa* genome.

fewer *Populus* MYB proteins than expected, given the whole genome duplication event (five *Arabidopsis*, three *P. trichocarpa*, three *V. vinifera*). These findings lend support to the model of gene loss in the *Populus* lineage or gene duplication in the *Arabidopsis* lineage following divergence from the last common ancestor.

Remarkably, several clades do not include any *Arabidopsis* R2R3-MYB proteins but only members from *Populus* and *Vitis* (Fig. 2). This suggests that the genes in these clades may have specialized roles that were either lost in *Arabidopsis* or acquired in the *Populus* and *Vitis* lineages after divergence from the last common ancestor with *Arabidopsis*. It remains to

be determined whether the absence of *Arabidopsis* genes in these clades extends to other members of Eurosids II or whether it is something particular to the *Arabidopsis* genome.

PopGenExpress, an Affymetrix Microarray-Based Compendium of *Populus* Transcript Abundance, Provides Insights into R2R3-MYB Gene Expression and Diversification

Affymetrix Poplar Genome Arrays were used to assess the transcript abundance of 180 R2R3-MYB-encoding genes (Supplemental Table S1). There were

no probe sets on the array corresponding to the remaining R2R3-MYB-encoding transcripts. Transcript abundance for the R2R3-MYB-encoding genes was assessed in biological triplicate RNA samples extracted from seedlings grown under different light regimes, young leaves, mature leaves, roots, xylem, female catkins, and male catkins. The compendium of data derived from these experiments is referred to as the *Populus* Gene Expression (PopGenExpress) data set.

As is commonly the case for genes encoding transcription factors, many of the *P. trichocarpa* R2R3-MYB-encoding genes had low transcript abundance levels, as determined by the Affymetrix microarray analysis. Nevertheless, distinct transcript abundance patterns were readily identifiable in the PopGenExpress data set for all 180 of the R2R3-MYB probe sets on the microarray. Groups of MYB-encoding genes showed preferential accumulation of transcripts in a given organ or tissue or under a specific condition (Fig. 4). In fact, the majority (75%) of *Populus* R2R3-MYB-encoding genes exhibited transcript abundance profiles that had marked peaks in transcript abundance in only one distinct condition in the current PopGenExpress data set. This suggests that R2R3-MYB proteins function as regulators of processes that are limited to discrete cells, organs, or conditions.

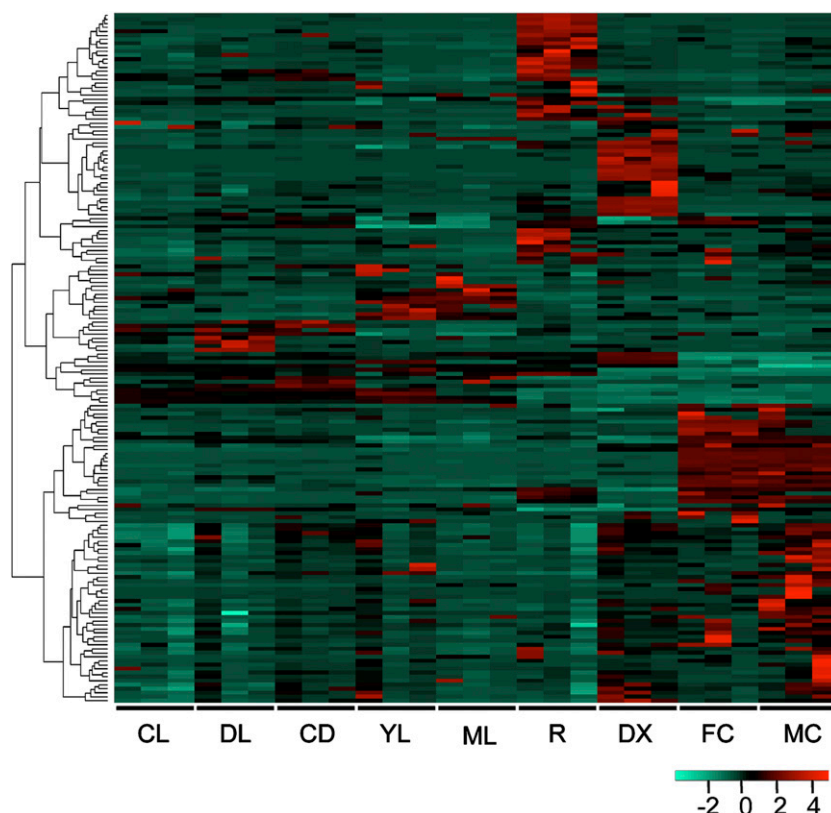
In keeping with their roles as regulators in plant-specific processes, 23 of 180 *Populus* R2R3-MYB-encoding genes showed the highest level of transcript abundance in differentiating xylem, a tissue that gives

rise to the woody stem characteristic of trees like *Populus*. A further 29 R2R3-MYB genes (16%) had the greatest accumulation of transcripts in roots. Remarkably, none of these genes encoded a protein with high sequence similarity to WEREWOLF, which is involved in the determination of epidermal cell fate in *Arabidopsis* roots (Tominaga et al., 2007). It may be that one of the other R2R3-MYB genes with high transcript abundance in *Populus* roots plays this role.

Strikingly, seven of the *Populus* MYB family members with the most abundant expression in roots encode proteins in a clade with members of the Blind subfamily of R2R3-MYB proteins (C1). Blind was originally identified on the basis of its role in affecting plant aerial architecture by controlling axillary branch formation in tomato (*Solanum lycopersicum*; Schmitz et al., 2002). Blind-related proteins in *Arabidopsis* have demonstrated roles in the regulation of axillary meristems (AtMYB37, AtMYB38, and AtMYB84; Keller et al., 2006; Muller et al., 2006) and in root development (AtMYB68; Feng et al., 2004). It may be that the Blind-related proteins that are expressed in *Populus* roots play a similar role in shaping root architecture. Similarly, it is possible that some of the Blind-related genes in *P. trichocarpa* may exhibit transcript accumulation in axillary buds and meristems. The continued expansion of the PopGenExpress data set will allow for testing of such hypotheses.

Approximately 28% (50 of 180) of the *Populus* R2R3-MYB-encoding genes had the highest transcript abun-

Figure 4. *Populus* R2R3-MYB genes exhibit differential expression across a range of tissues, organs, and treatments. The patterns of relative transcript accumulation of each of 180 R2R3-MYB genes and five 3R-MYB genes as determined by microarray analysis are presented as a heat map, with red indicating higher levels and green indicating lower levels of transcript accumulation. Each column represents a discrete biological sample, and all treatments are presented as biological triplicates. CL, Seedlings grown in continuous light; DL, seedlings grown in continuous darkness and then transferred to light for 3 h; CD, seedlings grown in continuous darkness; YL, young leaf; ML, mature leaf; R, root; DX, differentiating xylem; FC, female catkins; MC, male catkins. Data are normalized within each row.



dance in catkins. Twenty-nine of these 50 genes (58%) showed the highest transcript accumulation in male catkins, seven (14%) had the highest accumulation in female catkins, and the remaining 14 (28%) had approximately equal transcript accumulation in male and female catkins. The genes showing the highest transcript accumulation in both male and female catkins represent the largest group of R2R3-MYB transcripts that accumulate in more than one condition in this data set.

Twelve of the R2R2-MYB-encoding genes with the highest transcript accumulation in flowers fell into four clades (C11, C19, C38, and C39) that contained Arabidopsis R2R3-MYB family members with known roles in plant reproductive biology. These included Arabidopsis R2R3-MYB family members implicated in anther development (AtMBY21 [Shin et al., 2002], AtMYB24 [Yang et al., 2007], AtMYB33 [Gocal et al., 2001], AtMYB65 [Gocal et al., 2001], and AtMYB103 [Zhang et al., 2007]), pollen tube guidance and synergid formation (AtMYB98; Kasahara et al., 2005), and sperm cell formation (AtMYB125; Durbarry et al., 2005). The *Populus* counterparts of these MYB family members, which share both high sequence similarity and expression profiles, are good candidates for future studies aimed at developing a better mechanistic understanding of floral development in *Populus*. Characterization of these family members would be an ideal starting point in the dissection of sex determination in the dioecious *Populus* lineage.

In addition to groups of genes that had similar transcript abundance profiles but were relatively phylogenetically distinct, several phylogenetic clades were characterized by having members that largely shared the same transcript abundance profile. Similar transcript abundance patterns were observed even between Arabidopsis and *Populus* members of the clade. Prominent among these clades were those that included R2R3-MYB-encoding genes related to those previously implicated in the regulation of phenylpropanoid metabolism.

***Populus* R2R3-MYB Proteins Related to Those Implicated in the Regulation of Phenylpropanoid Metabolism Tend to Share Transcript Abundance Profiles**

Many R2R3-MYB proteins modulate the expression of genes encoding enzymes involved in various facets of phenylpropanoid metabolism. Phenylpropanoid metabolism generates a vast array of compounds that are important for a diversity of plant functions, including resistance to herbivore and pathogen attacks (Peters and Constabel, 2002; Miranda et al., 2007), and for the construction of structural components of the plant body (Boerjan et al., 2003; Deluc et al., 2006). Phenylpropanoid metabolism is particularly important in tree species, which make use of phenylpropanoid-derived metabolites to elaborate a diversity of soluble defense compounds as well as insoluble tannins that function as a durable resistance against herbivores and

pathogens (Peters and Constabel, 2002). Moreover, trees like *Populus* have a woody stem composed of up to 30% phenylpropanoid-derived lignins, which provide structural integrity, water transport capacity, and defense against degradation for this key portion of the tree body. In keeping with the importance of maintaining a diverse and robust phenylpropanoid metabolism in trees, genes encoding enzymes of phenylpropanoid metabolism are overrepresented in the *Populus* genome relative to the Arabidopsis genome (Tuskan et al., 2006). On the basis of the analysis of *Populus* genes predicted to encode R2R3-MYB proteins, the trend in diversifying genes encoding enzymes in the phenylpropanoid pathway also seems to extend to genes encoding regulators of this pathway.

Many of the R2R3-MYB proteins implicated in the control of phenylpropanoid metabolism group into specific clades on the basis of the facet of phenylpropanoid metabolism they regulate. For example, clade 10 includes R2R3-MYB family members implicated in the regulation of genes encoding lignin biosynthetic enzymes (Fig. 5A). This clade includes *Pinus taeda* MYB4, which is expressed in cells undergoing lignification and alters the accumulation of transcripts corresponding to genes encoding lignin biosynthetic enzymes (Patzlaff et al., 2003). Other members of this clade have been shown to function in an almost identical fashion, with expression in differentiating xylem cells and capacity to alter lignin biosynthesis. These include AtMYB46 (Zhong et al., 2007), *Eucalyptus gunnii* MYB2 (Goicoechea et al., 2005), and *Picea glauca* MYB4 (Bedon et al., 2007).

In our phylogeny, two *V. vinifera* proteins and four *P. trichocarpa* proteins group in the lignification-related R2R3-MYB clade. The *P. trichocarpa* genes encoding these proteins are located on LG_1 (*P. trichocarpa* MYB002 and *P. trichocarpa* MYB003) and LG_IX (*P. trichocarpa* MYB020 and *P. trichocarpa* MYB021) in regions that are thought to be the paralogous product of the recent salicoid whole genome duplication event (Tuskan et al., 2006). The *P. trichocarpa* proteins are most similar to *E. gunnii* MYB2 and to the *V. vinifera* members of this clade. Three of the four *Populus* R2R3-MYB genes exhibit high levels of transcript accumulation in xylem tissue (Fig. 5B), suggesting that function in this tissue has been retained for most family members since the duplication event. The transcript abundance profile also suggests that, like their counterparts in other plant species, these transcription factors also function in xylem-based processes, perhaps also regulating genes encoding enzymes of the lignin biosynthetic pathway. The retention of these apparent redundant functions in *Populus* speaks to the importance of regulating the elaboration of diverse xylem cells in a woody angiosperm and the necessity of the fine control of lignin biosynthesis associated therewith (Karpinska et al., 2004).

R2R3-MYB proteins are also well known regulators of anthocyanin biosynthesis in fruit, flowers, and leaves. PRODUCTION OF ANTHOCYANIN PIGMENT

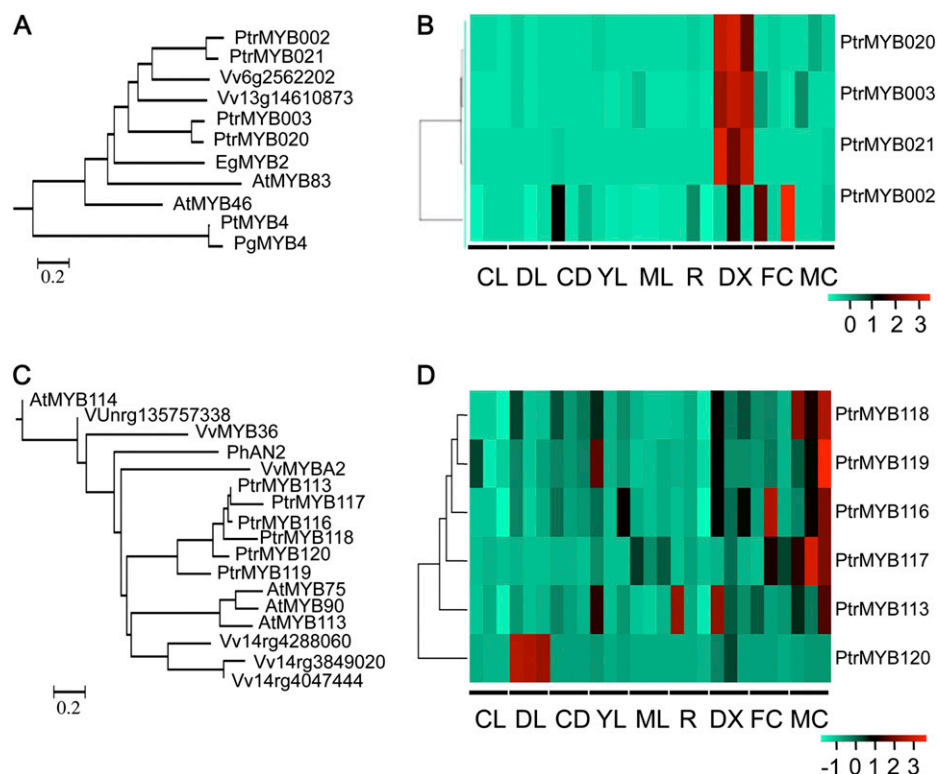


Figure 5. PtrR2R3-MYB genes show conserved patterns of transcript accumulation across tissues. A, Clade 10 includes R2R3-MYB genes isolated from the wood-forming tissues of a number of species, including *P. glauca* (Pg), *P. taeda* (Pt), *E. gunnii* (Eg), *V. vinifera* (Vv), and *Arabidopsis* (At) as well as four previously uncharacterized R2R3-MYB genes from *P. trichocarpa* (Ptr). B, The relative transcript accumulation of each of the PtrR2R3-MYB genes in clade 10 as determined by microarray analysis. C, Clade 27 includes several well-known R3R3-MYB genes with demonstrated roles in anthocyanin biosynthesis in a variety of organisms, including AtPAP1/MYB75, AtPAP2/MYB90, and *P. hybrida* ANTHOCYANIN2 (PhAN2) as well as six previously uncharacterized PtrR2R3-MYB genes. D, The relative transcript accumulation of each of the PtrR2R3-MYB genes in clade 27 as determined by microarray analysis. The scale bars under the trees represent 0.2 substitutions. The heat maps are clustered by Pearson correlation coefficient. Red indicates higher levels and green represents lower levels of transcript accumulation. CL, Seedlings grown in continuous light; DL, seedlings grown in continuous darkness and then transferred to light for 3 h; CD, seedlings grown in continuous darkness; YL, young leaf; ML, mature leaf; R, root; DX, differentiating xylem; FC, female catkins; MC, male catkins.

(PAP) proteins, AtMYB75/PAP1 and AtMYB90/PAP2, are two of the best characterized *Arabidopsis* R2R3-MYB proteins involved in this process. AtMYB75/PAP1 is essential for both Suc-induced (Teng et al., 2005) and light-induced (Cominelli et al., 2008) anthocyanin accumulation. These genes form a clade (clade 27) that also includes AtMYB113 and AtMYB114, which regulate late steps in anthocyanin biosynthesis in *Arabidopsis* (Gonzalez et al., 2008), and *Petunia* × *hybrida* ANTHOCYANIN2, which regulates anthocyanin in flowers (Quattrocchio et al., 1999; Fig. 5C). Six *Populus* R2R3-MYB proteins grouped with this clade. Four of the genes encoding these proteins, *PtrMYB116*, *PtrMYB117*, *PtrMYB118*, and *PtrMYB119*, all had high levels of transcript accumulation in the male catkins (Fig. 5D). The male catkins of *Populus* are characteristically a deep red color attributable to the abundance of anthocyanin-rich pollen grains. Anthocyanin pigments provide protection against damaging levels of UV radiation (Cominelli et al., 2008) and also function as precursors to conjugates that protect against path-

ogens and herbivory (Peters and Constabel, 2002). The apparently redundant activity of four R2R3-MYB genes in male catkins underlines the importance of regulating the biosynthesis of these protectants in reproductive tissue. *PtrMYB120* has the highest level of transcript accumulation in seedlings grown in continuous darkness and then moved into the light for 3 h; therefore, it may play a role in evoking anthocyanin biosynthesis in vegetative tissues to protect them from the deleterious effects of UV light (Fig. 5D). *PtrMYB113* shows low transcript accumulation throughout the tissues and organs examined and may function to regulate anthocyanin biosynthesis in response to a stimulus that was not included in this study.

The genes encoding the proteins in the clade implicated in the regulation of anthocyanin biosynthesis have a distinctive arrangement in the *Arabidopsis*, *V. vinifera*, and *P. trichocarpa* genomes. In all three organisms, the genes are present as tandem duplications that appear to have arisen since they last shared a

common ancestor (Fig. 5C; Supplemental Fig. S1). Notably, the R3 MYB repeat in *P. trichocarpa* and *V. vinifera* R2R3-MYB proteins in this clade is modified relative to the corresponding motif in the Arabidopsis and *P. hybrida* proteins. This modification takes the form of a four-amino acid addition (QV_k/qM) directly preceding the first conserved Trp in the R3 repeat (Supplemental Fig. S2A). These additional amino acids are encoded by sequences present at the 3' end of the second exon. Based on an alignment of the predicted mRNA molecules for the Arabidopsis, *V. vinifera*, and *P. trichocarpa* genes in this clade, it does not appear that there has been an error in splice site prediction (Supplemental Fig. S2B). That is, the additional amino acids in the *Populus* R3 domain appear to be bona fide components of the motif. Given the role of this motif in protein-DNA interactions, the additional four amino acids in the *Populus* proteins could affect DNA binding. The fact that this motif is present in all six of the *Populus* members of the clade suggests that they are likely to bind to similar targets, but it remains to be determined if their binding specificity or selectivity differs from that of their Arabidopsis counterparts. Future studies could examine this possibility and use it as the basis to explore the coevolution of DNA-binding domains relative to their cognate cis-acting DNA binding sites.

The high degree of redundancy within those clades in which genes share highly similar transcript abundance profiles is consistent with the hypothesis that subfunctionalization has occurred, with individual family members assuming nonredundant functions in the same tissue. In some cases, subfunctionalization

may have resulted in one of the MYB proteins acting as an activator of gene expression and another acting as a repressor. Coexpression of such antagonistic pairs of MYB proteins can produce a "gearing mechanism" in which the regulation of shared target genes is a function of the relative abundance of a strong activator relative to a weaker one (Moyano et al., 1996). Alternatively, the high degree of redundancy within such clades may reflect the fact that there has not been adequate time for selection to purge one of the paralogs. It must be noted that genetic distance between paralogous pairs of R2R3-MYB genes was not a good predictor of the Pearson correlation coefficient describing their expression profiles (Supplemental Fig. S3). Namely, paralogous pairs separated by shorter genetic distances were no more likely to be coexpressed than were pairs separated by longer genetic distances.

The *Populus* Electronic Fluorescent Pictograph Browser Facilitates Rapid Hypothesis Testing Related to MYB Expression

Identification of *Populus* R2R3-MYB genes with transcript abundance patterns or gene products that are phylogenetically close to MYB proteins with known function from other species provides candidates for future studies aimed at thoroughly dissecting MYB function. Such studies would benefit from tools that enabled more intuitive representations of transcript abundance patterns from the PopGenExpress compendium, so that rapid comparisons could be made with putative orthologs from better characterized

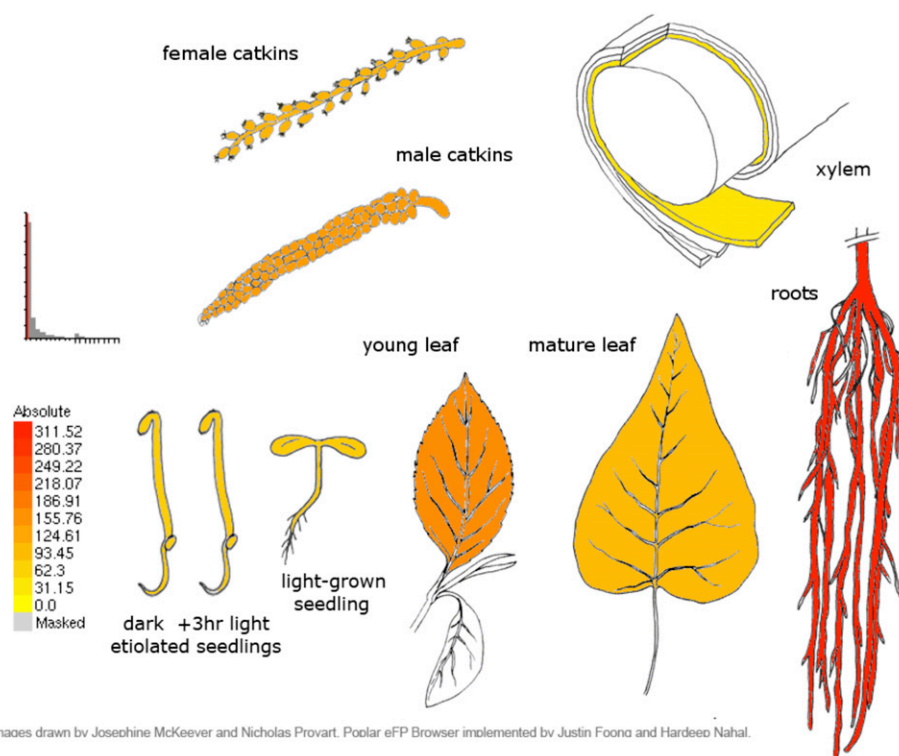


Figure 6. eFP display of transcript accumulation patterns across a variety of *Populus* organs and treatments. Poplar eFP browser presents the transcript accumulation pattern of *PtrMYB025* in a variety of tissues and organs. In all cases, red indicates higher levels of transcript accumulation and yellow indicates a lower level of transcript accumulation.

species such as *Arabidopsis*. To enable community-wide, simple, graphical representation of PopGenExpress transcript abundance data, a Web-based tool was devised, the *Populus* Electronic Fluorescent Pictograph (eFP) browser (Fig. 6; <http://www.bar.utoronto.ca/efppop/cgi-bin/efpWeb.cgi>). The *Populus* eFP browser is based on eFP tools for *Arabidopsis* and *Mus musculus* (Winter et al., 2007). For the *Populus* eFP browser, diagrams of poplar tissues, organs, or growth conditions are shaded, with colors corresponding to the quantity of transcript for a given gene under that condition.

The *Arabidopsis* eFP browser tool has already proven to be highly useful in the display and interpretation of *Arabidopsis* transcript abundance data. Use of the comparable tool for *Populus* (Fig. 6) will also enable straightforward, intuitive representation of *Populus* transcript abundance data as well as simple comparison of transcript abundance distribution for a given *Populus* gene against its putative *Arabidopsis* counterpart. Comparison of eFP browser profiles for homologous *Arabidopsis* and *Populus* genes facilitates direct testing of the hypothesis that the homologs may respond to the same stimuli or play a role in the same processes in their respective species. This simple analysis can be extended to any pair of potentially orthologous genes, across the entire set of genes probed by the Affymetrix array. To facilitate such hypothesis testing and development, all *Arabidopsis* and *P. trichocarpa* orthologs have been precomputed using the OrthoMCL algorithm and are displayed as links in the eFP browser.

CONCLUSION

Detailed annotation and phylogenetic analysis of the entire complement of *P. trichocarpa* R2R3-MYB genes and their protein products reveal the striking diversification that has occurred in this gene family in *Populus*. Some of this diversification is attributable to genome duplication, but unequal expansion in particular clades and the manifestation of entire clades lacking *Arabidopsis* family members suggest that some of the diversification in *Populus* R2R3-MYB family members may contribute to lineage-specific phenotypic innovations. Here, we have identified some of the family members that may contribute to these innovations, through an examination of both the R2R3-MYB phylogeny and patterns of transcript abundance. These genes will form the basis for future hypothesis tests involving gain-of-function and loss-of-function studies aimed at clarifying their roles in *Populus* growth, development, and survival.

We also provide a collection of data and an associated bioinformatics tool that enable the research community to examine, visualize, and formulate hypotheses based on transcript abundance of R2R3-MYB-encoding genes or, indeed, any other gene in *Populus* that is represented on the Affymetrix Poplar GeneChip. By precomputing *Arabidopsis*-*Populus* orthologs, we also

enable easy cross-species expression viewing to identify the true functional ortholog in *Populus* of a given *Arabidopsis* gene, if it exists. The gene expression database is expandable and will acquire greater value as other researchers add their GeneChip data to the core compendium we have established. This will add greatly to the expanding toolbox available to characterize the molecular mechanisms underpinning the basic biology of an ecologically dominant and economically important tree genus.

MATERIALS AND METHODS

Plant Material

Plant material was collected from clonally propagated, 8-week-old *Populus balsamifera* saplings (clone 1006; Alberta Pacific Forest Industries) grown in a climate-controlled growth chamber (mature leaf, young leaf, root, differentiating xylem), or from *P. balsamifera* seeds (etiolated light and dark seedlings; seed lot no. 20071015; National Tree Seed Centre), or from mature *P. balsamifera* trees grown by Alberta Pacific Forest Industries in a field trial in Grassland, Alberta, Canada (male and female catkins). Trees established in the growth chamber were grown in Sunshine Mix (Sun Gro Horticulture) with a 16-h photoperiod, a maximum daytime temperature of 22°C, and a minimum nighttime temperature of 17°C. All tissues were collected 8 h into the light phase during a 16-h/8-h light/dark cycle, except for the midnight samples, which were collected at 4 h after the shift from light to dark in the same cycle. All tissues were collected from saplings without water limitations. For the comparison of dark-grown seedlings versus those grown in the dark and then exposed to light for 3 h, seeds were germinated in the dark in a growth chamber on wetted filter paper on petri plates with a constant temperature of 21°C for 5 d. On the 6th d, half of the plates were exposed to light (150 μ mol) for 3 h. At this time, seedlings were collected from plates exposed to light and from plates in continuous darkness. All collected plant materials were flash frozen in liquid nitrogen upon harvesting and stored at -80°C until RNA was extracted. Each sample comprised pooled material from three individuals, except for the seedling samples, which comprised pooled material from 20 individuals. Mature leaf samples comprised the first fully expanded leaf of three saplings, including the petiole. Young leaf samples included the first leaf, with its petiole, that was completely uncurled but was still shiny and much smaller than the mature leaves. Root samples included the distal 15 cm of well-rinsed root mass. Differentiating xylem was collected from the bottom 6 inches of the stem by peeling off the bark and immediately scraping the surface of the exposed wood into microcollection tubes containing liquid nitrogen. Seedlings were grown for 5 d in the dark; on the 6th d, half of the seedlings were transferred to the light and samples (comprising entire seedlings) were collected at 30 min after transfer to light. Male and female catkins were collected on April 30, 2007.

Phylogenetic Analysis

Arabidopsis (*Arabidopsis thaliana*) R2R3- and 3R-MYB gene identifiers were obtained from Stracke et al. (2001), and the corresponding protein sequences were downloaded from The *Arabidopsis* Information Resource (<http://Arabidopsis.org>; Rhee et al., 2003; Supplemental Table S3). Different identifiers have been used for AtMYB8 (At1g35515), AtMYB39 (At4g17785), and AtMYB118 (At3g27785) in this work than by Stracke et al. (2001).

Gene identifiers for 94 *Vitis vinifera* R2R3-MYB genes were obtained from Matus et al. (2008), and the corresponding protein sequences were downloaded from the International Grape Genome Program's (IGGP) Web site (http://www.genoscope.cns.fr/externe/English/Projets/Projet_ML/projet.html). It is important to note that while Matus et al. (2008) identified 108 putative R2R3-MYB-encoding genes, careful scrutiny of the coding sequences revealed that 15 of these genes actually represent single-repeat MYB proteins and so were excluded from the analysis described here. An additional 25 R2R3- and five 3R-MYB genes were identified on the International Grape Genome Program's Web site using the search terms "R2R3" and "MYB transcription factor" (Supplemental Table S4).

Populus trichocarpa MYB gene models were retrieved from the Joint Genome Institute *P. trichocarpa* version 1.1 Web site (http://genome.jgi-psf.org/Poptr1_1/Poptr1_1.home.html). Putative MYB genes in the *P. trichocarpa* genome were identified using the PAC version 0.1 Ortholog Finder using Arabidopsis R2R3-MYBs as reference (Supplemental Table S1). MYB gene models were identified using the KOG keyword "MYB." All *P. trichocarpa* and *V. vinifera* models were manually inspected to ensure that the putative gene models contained two or three MYB DBDs and that the gene models mapped to unique loci in their respective genomes. It is important to note that a proportion of the 21 *P. trichocarpa* R2R3-MYB genes that have not been assigned to a LG may be alleles of genes already placed on a LG, but as this has not yet been resolved empirically, these 21 genes were treated as distinct loci.

An additional 22 R2R3-MYB transcription factors from other tree species were included in the phylogeny: seven from *Pinus taeda*, 13 from *Picea glauca*, and two from *Eucalyptus gunnii* (Supplemental Table S5). A further 32 "landmark" MYB proteins from a variety of other organisms were also included in the analysis (Supplemental Table S6; Jiang et al., 2004). Sequences were retrieved from the National Center for Biotechnology Information protein database (NCBI Entrez; <http://www.ncbi.nlm.nih.gov/sites/entrez>).

Phylogenetic analysis included the above 506 R2R3-MYB proteins and 15 3R-MYB proteins. The full-length amino acid sequences were aligned with MAFFT using the G-INS-I algorithm (Katoh et al., 2005). A neighbor-joining tree was constructed using MEGA 4 (Tamura et al., 2007) with settings for Jones-Taylor-Thornton substitution model and a Gamma parameter of 1.0 to allow for the uneven rates of substitution across the length of the protein, including the highly conserved N-terminal DBD and the more divergent C-terminal activation domain. Pairwise gap deletion was used to ensure that the C-terminal residues, which are more divergent in MYB proteins, could contribute to the topology of the neighbor-joining tree.

RNA Extraction and Microarray Hybridization

Plant material was ground to a fine powder under liquid nitrogen, and total RNA was extracted from each sample using the procedure described by Chang et al. (1993) for all materials except the seedling samples, which were extracted using the Trizol method (Invitrogen). RNA quality was determined electrophoretically. For each sample, 10 µg of total RNA was reverse transcribed, labeled, and hybridized to the Poplar Genome Array according to the manufacturer's protocols (Affymetrix) at the Centre for Applied Genome Evolution and Function at the University of Toronto. The Poplar Genome Array includes 61,251 probe sets representing more than 56,055 transcripts (Affymetrix). The GeneChip probe design is based on the Joint Genome Institute's *P. trichocarpa* genome project's predicted gene set version 1.1 and all publicly available EST and mRNA sequences for all *Populus* species available through UniGene Build #6 and GenBank in the spring of 2005. The array probes for transcripts derived from 13 *Populus* species in addition to the fully sequenced *P. trichocarpa* genome. For each condition, RNA from three replicate biological samples was extracted and hybridized to a Poplar GeneChip.

Microarray Analysis

GeneChip data analysis was performed using the BioConductor suite (Gentleman et al., 2004) in R (a language and environment for statistical computing; <http://www.R-project.org>) using the Affy package (Gautier et al., 2004). Preprocessing of the arrays was done using GC-robust multiarray analysis (Gentleman et al., 2004). Probe sets corresponding to the putative R2R3-MYB and 3R-MYB transcription factors were identified using the Probe Match tool on the NetAffx Analysis Centre Web site (Table I; <http://www.affymetrix.com/analysis/index.affx>). The transcript abundance levels for probe sets corresponding to the putative MYB genes in the *P. trichocarpa* genome were extracted from the complete data set, and the probe sets were then clustered using hierarchical clustering based on Pearson correlation coefficients (Heatplus; <http://bioconductor.org/packages/2.3/bioc/html/Heatplus.html>).

Poplar eFP Browser

A Poplar eFP browser (<http://www.bar.utoronto.ca/efppop/cgi-bin/efpWeb.cgi>) was developed based on the Bio-Array Resource database framework described by Toufighi et al. (2005) and the eFP engine developed by Winter et al. (2007). Briefly, database tables were generated using MySQL to archive meta information for the samples used to produce the transcriptome data in

this study as well as to store the expression data themselves, after the MIAME (for minimum information about a microarray experiment) convention (Brazma et al., 2001). This database may be queried through other tools described by Toufighi et al. (2005), such as Expression Browser, Project Browser, and Expression Angler for identifying coexpressed genes of interest (Toufighi et al., 2005). In the case of the poplar gene expression database, we normalized the Affymetrix data using the GCOS algorithm, with a TGT value of 500. Diagrammatic representations of poplar were generated and processed as described by Winter et al. (2007) to create an input for the eFP browser. In addition, an XML control file was created to instruct the eFP engine for proper functioning. Finally, Arabidopsis-*Populus* orthologs based on the *P. trichocarpa* gene models were computed using the OrthoMCL algorithm (Li et al., 2003). These were stored in a separate database along with precomputed Arabidopsis-*Populus* sequence alignments, generated with MAFFT using the G-INS-I algorithm (Katoh et al., 2005) and displayed on demand using Nigel Brown's MView (Brown et al., 1998) program.

Sequence data from this article can be found in the Joint Genome Institute's *Populus trichocarpa* v1.1 library (http://genome.jgi-psf.org/Poptr1_1/Poptr1_1.home.html), in Genoscope's *Vitis vinifera* genome library (<http://www.genoscope.cns.fr/spip/Vitis-vinifera-e.html>), and in the GenBank data library (for all species other than *P. trichocarpa* and *V. vinifera*) under the accession numbers listed in Supplemental Tables S1, S3, S4, S5, and S6. Microarray data from this article can be found in the GEO database under accession number GSE13990.

Supplemental Data

The following materials are available in the online version of this article.

Supplemental Figure S1. Phylogenetic relationships and subgroup designations in MYB proteins in *Populus*, *Vitis*, and Arabidopsis.

Supplemental Figure S2. PtrR2R3-MYB genes in clade 27 have a modified R3 DBD.

Supplemental Figure S3. Pairwise Pearson correlation coefficients of the expression profiles of 56 paralogous R2R3-MYB gene pairs as a function of the genetic distance separating each pair.

Supplemental Table S1. R2R3- and 3R-MYB-encoding genes from *P. trichocarpa*.

Supplemental Table S2. Membership of subgroups on the *P. trichocarpa*, Arabidopsis, and *V. vinifera* phylogenetic tree.

Supplemental Table S3. R2R3- and 3R-MYB encoding genes from Arabidopsis.

Supplemental Table S4. R2R3- and 3R-MYB-encoding genes from *V. vinifera* ('gene model identified by Matus et al. [2008]).

Supplemental Table S5. R2R3- and 3R-MYB-encoding genes from a variety of tree species.

Supplemental Table S6. Landmark R2R3- and 3R-MYB-encoding genes from a variety of plant species.

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