Differentiating Arabidopsis Shoots from Leaves by Combined YABBY Activities

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In seed plants, leaves are born on radial shoots, but unlike shoots, they are determinate dorsiventral organs made of flat lamina. YABBY genes are found only in seed plants and in all cases studied are expressed primarily in lateral organs and in a polar manner. Despite their simple expression, Arabidopsis thaliana plants lacking all YABBY gene activities have a wide range of morphological defects in all lateral organs as well as the shoot apical meristem (SAM). Here, we show that leaves lacking all YABBY activities are initiated as dorsiventral appendages but fail to properly activate lamina programs. In particular, the activation of most CINCINNATA-class TCP genes does not commence, SAM-specific programs are reactivated, and a marginal leaf domain is not established. Altered distribution of auxin signaling and the auxin efflux carrier PIN1, highly reduced venation, initiation of multiple cotyledons, and gradual loss of the SAM accompany these defects. We suggest that YABBY functions were recruited to mold modified shoot systems into flat plant appendages by translating organ polarity into lamina-specific programs that include marginal auxin flow and activation of a maturation schedule directing determinate growth.

INTRODUCTION

Leaves are determinate laminar structures specialized for photosynthesis. Evidence in the fossil record suggests that seed plant leaves evolved from lateral branch systems (Galtier, 1981; Stewart and Rothwell, 1993; Beerling and Fleming, 2007; Sanders and Rothwell, 2009). Over time, the ancestral radial, three-dimensional lateral shoot systems evolved to become determinate, planar, dorsiventral, and eventually laminar. This would have required mechanisms to repress radial, axial growth and promote laminar growth. Lamina growth facilitated the development of specialized leaf surfaces, with leaves of many seed plant species having one surface specialized for light capture and the other for gas exchange.

Leaves of seed plants are derived from the periphery of the shoot apical meristem (SAM) and display a distinct adaxial-abaxial axis. This asymmetry is thought to reflect inherent positional differences in the developing organ relative to the SAM from which it is derived; the adaxial side is adjacent to the meristem, while the abaxial side faces away from the meristem. In classical experiments in which an incision was made between the SAM and an incipient leaf primordium, the isolated leaf primordium developed as a radial unifacial organ, indicating not only that adaxial-abaxial polarity establishment requires communication with the SAM but that adaxial-abaxial polarity is necessary for lamina growth (Sussex, 1954). Later observations of ectopic lamina development in Antirrhinum phantastica mutants led to the proposal that juxtaposition of adaxial and abaxial cell types results in lamina growth (Waites and Hudson, 1995).

Experiments in model angiosperm species have identified several families of transcription factors, some of which are regulated by small RNAs, that direct adaxial-abaxial polarity establishment, or its interpretation, and in so doing promote laminar growth (Canales et al., 2005; Chitwood et al., 2007). Adaxial fates in angiosperm leaves are regulated by the activities of the AS2/ARP (PHANTASICA-related) and class III HD-Zip transcription factors and trans-acting small interfering RNAs, which are generated through the miR390-TAS3-RDR6 pathway (Waites and Hudson, 1995; McConnell and Barton, 1998; Emery et al., 2003; Chitwood et al., 2007; Iwakawa et al., 2007). In Arabidopsis thaliana, abaxial fates are the result of the activities of the KANADI, YABBY, and AUXIN RESPONSE FACTOR (ARF3/4) transcription factor families and the miR165/166 small RNAs (Eshed et al., 1999, 2001; Sawa et al., 1999a; Siegfried et al., 1999; Kerstetter et al., 2001; McConnell et al., 2001; Juarez et al., 2004; Pekker et al., 2005). Homologs of nearly all of these genes...
can be found in the genomes of *Selaginella moellendorffii* (lycophyte) and *Physcomitrella patens* (moss), demonstrating that most of the gene families identified as important for leaf polarity and lamina growth existed long before seed plant leaves evolved (Harrison et al., 2005; Floyd and Bowman, 2006, 2007; Floyd et al., 2006; Prigge and Clark, 2006). This suggests that most of the genetic machinery for seed plant leaf polarity establishment was coopted from preexisting genetic programs operating in plants with indeterminate branching radial shoot systems; however, neofunctionalization following duplication may have been critical. The lone known exception is the YABBY gene family, which is seed plant–specific; thus, its evolutionary history coincides with the origin of leaves in seed plants (Floyd and Bowman, 2007; Figure 1). YABBY genes have unique expression patterns that include exclusion from apical meristems, activation in initiating lateral organ primordia, and, often, asymmetric restriction to the abaxial domain of eudicot primordia but to the adaxial domain of initiating maize (*Zea mays*) leaves (Sawa et al., 1999a; Siegfried et al., 1999; Golz et al., 2004; Juarez et al., 2004).

YABBY genes have been identified in all seed plants examined, with most eudicotyledonous angiosperms possessing five different classes (Bowman and Smyth, 1999; Yamada et al., 2004; Lee et al., 2005). The *Arabidopsis* genome contains six YABBY genes (*FILAMENTOUS FLOWER* [FIL], *CRABS CLAW* [CRC], *INNER NO OUTER* [INO], *YABBY2* [YAB2], YAB3, and YAB5), with FIL and YAB3 the result of a recent duplication (Bowman and Smyth, 1999; Sawa et al., 1999b; Siegfried et al., 1999; Villanneva et al., 1999; Lee et al., 2005). The expression of two family members, CRC and INO, is restricted to floral organs (Bowman and Smyth, 1999; Villanneva et al., 1999). In contrast, FIL, YAB3, YAB2, and YAB5 are referred to as the “vegetative YABBY genes” of *Arabidopsis*, with FIL, YAB2, and YAB3 expressed in the abaxial domains of all leaf-derived organs, including cotyledons, leaves, and floral organs (Sawa et al., 1999a; Siegfried et al., 1999; Watanabe and Okada, 2003; Golz et al., 2004).

The molecular identification of YABBY genes, along with the discovery of their polar expression patterns, led to the proposal that YABBY factors promote abaxial cell fate (Eshed et al., 1999; Sawa et al., 1999b; Siegfried et al., 1999). A role in polar differentiation is supported by both gain- and loss-of-function data. For example, *Arabidopsis* loss-of-function alleles of CRC can result in adaxial carpel tissues developing in abaxial positions, while gain-of-function alleles of FIL and YAB3 promote the differentiation of abaxial tissues in adaxial positions (Eshed et al., 1999; Sawa et al., 1999b; Siegfried et al., 1999). Consistent with classical observations, expression of FIL and YAB3 is closely associated with lamina expansion in *Arabidopsis*, with boundaries of abaxial YABBY gene expression marking the abaxial–adaxial boundary (Siegfried et al., 1999; Kumaran et al., 2002; Eshed et al., 2004). Expression of FIL and YAB3 in leaf primordia displays a longitudinal gradient, presumably following the cell division arrest front, which passes from leaf tip to base (Nath et al., 2003). Previous studies have demonstrated a partial loss of polar differentiation in leaves and other lateral organs of YABBY mutants, with both adaxial and abaxial tissues being affected, implying nonautonomous YABBY gene activity in the adaxial leaf domain (Siegfried et al., 1999).

![Figure 1. Phylogenetic Distribution of Angiosperm Leaf Polarity Genes.](image)
et al., 1999; Kumaran et al., 2002; Golz et al., 2004; Stahle et al., 2009). Furthermore, loss of YABBY activity results in altered anatomy at the margin of Antirrhinum leaves (Golz et al., 2004). The implications for a role for YABBY genes in marginal patterning and growth are intriguing in light of recent evidence for the importance of marginal auxin transport and PIN1-mediated maxima in the patterning of leaves in Cardamine and Solanum (Scarpella et al., 2006; Barkoulas et al., 2008; Koenig et al., 2009). It is unknown how loss of YABBY function might affect important auxin-mediated processes in leaf margins.

Several lines of evidence suggest that the role of YABBY genes extends beyond promoting abaxial identity and laminar growth. Based on nonautonomous phenotypic defects in both loss- and gain-of-function alleles, YABBY gene activity has been implicated in communication between developing leaves and the SAM in both Arabidopsis and Antirrhinum (Eshed et al., 2004; Golz et al., 2004; Goldshmidt et al., 2008; Stahle et al., 2009) and in downregulating class I KNOX expression in leaves of Arabidopsis (Kumaran et al., 2002). Thus YABBY genes are implicated in both promoting polarity and laminar growth as well as repressing SAM-patterning genes.

Since at least some YABBY gene family members are abaxially expressed in Amborella trichopoda, the basal-most angiosperm taxon, abaxial expression may be the ancestral state in angiosperms (Yamada et al., 2004). However, abaxial expression is not universal within angiosperms, as some YABBY genes in Zea are expressed in a polar, but adaxial, pattern (Juarez et al., 2004). Furthermore, in restricted lineages of angiosperms, YABBY genes have been coopted for other developmental roles. For example, CRC orthologs are important for midrib development in grasses and for nectary development in core eudicots (Yamaguchi et al., 2004; Lee et al., 2005; Toriba et al., 2007). While no functional data are available for YABBY genes from basal angiosperms or gymnosperms, functional conservation in Arabidopsis and Antirrhinum and expression patterns in Amborella and Zea suggest an ancestral association of YABBY genes with leaf polarity, and by inference lamina growth within angiosperms.

Because of the unique association of the YABBY gene family with leaves in flowering plants and their phylogenetic restriction to the seed plant clade, understanding the role of YABBY genes in shoot development may provide insight into the fundamental nature of the angiosperm leaf and provide clues about the origin of leaves in the seed plant clade. Previous studies of YABBY gene function in leaves have been primarily limited to FIL and YAB3. Given similar expression patterns of all vegetative YABBY genes and the previously noted functional redundancy of FIL and YAB3, it is likely that YAB2 and YAB5 also play overlapping roles during leaf development (Siegfried et al., 1999). Therefore, we undertook a genetic approach to characterize Arabidopsis plants compromised in the function of all four vegetative YABBY genes (FIL, YAB3, YAB2, and YAB5) simultaneously. We demonstrate that YABBY genes govern embryo patterning and leaf lamina growth along the abaxial-adaxial boundary. In the absence of YABBY activities, leaf primordia maturation programs and restriction of SAM programs are partially lost; the leaves fail to activate early stages of lamina development marked by CINNATA-class TCP (CIN-TCP) activities and, instead, reactivate shoot programs marked by WUSCHEL (WUS) expression.

The developmental aberrations in YABBY loss-of-function mutants are both autonomous and nonautonomous in nature and are also accompanied by changes in the distribution and flow of auxin. Based on the new types of auxin flow patterns and the novel molecular composition of mutant leaves, we postulate that YABBY genes act as integrators of an ancestral shoot system genetic program, molding it into a leaf-specific program, and thus have been integral to the evolution of laminar organs in seed plants.

RESULTS

Expression of YAB2 and YAB5

To investigate YAB5 expression patterns, we constructed a promoter:β-glucuronidase (GUS) reporter gene using 4.1 kb of upstream sequence (extending from the YAB5 initiation codon to the next annotated gene). We constructed a similar reporter gene using 1.3 kb of the YAB2 upstream region. Like FIL and YAB3 (Figures 2A, 2D, 2G, and 2H), pYAB5:GUS and pYAB2:GUS are expressed in the abaxial domain of lateral organs (Figures 2I and 2J). Overall, the pYAB5:GUS construct was broadly expressed in young seedlings, with strongest expression in the petiole and midrib region (Figures 2B and 2E). Expression of the pYAB2:GUS construct was most pronounced in the petiole/midrib region (Figures 2C and 2F). It is notable that both pYAB2:GUS and pYAB5:GUS constructs continued to drive GUS expression in the midrib region of developed leaves (Figures 2E and 2F), while in leaves of equivalent age GUS expression in the yab3-2 allele was no longer apparent (Figure 2D). In several independent pYAB2:GUS and pYAB5:GUS transgenic lines, reporter gene expression was also observed in stem vascular tissues, an expression that was confirmed by RT-PCR (data not shown). Thus, FIL and YAB3 share overlapping expression domains with YAB2 and YAB5 in young leaf primordia.

Effects of Eliminating All YABBY Activity on Shoot Development

To eliminate all YABBY activity in young leaf primordia, mutations in YAB2 and YAB5 were identified and combined with strongest available alleles of FIL (fil-8), YAB3 (yab3-2), and CRC (crc-1; Alvarez and Smyth, 1999; Kumaran et al., 2002). Loss-of-function alleles of YAB2 and YAB5 genes were identified by screening TILLING lines (McCullum et al., 2000; Till et al., 2003). The yab5-1 allele is a Q>stop nonsense mutation in the highly conserved YABBY domain. The mutation in yab2-1 results in the loss of a splice site acceptor site and leads to a frameshift within the YABBY domain in the mRNA (see Supplemental Figure 1 online). Both mutations disrupt the YABBY domain, and based on phenotypes of similar alleles of FIL and CRC, they should be strong, likely null, alleles (Bowman and Smyth, 1999; Siegfried et al., 1999).

Leaves of homozygous yab2-1 and yab5-1 mutant lines and the yab2-1 yab5-1 double mutant exhibit a morphology similar to wild-type leaves (Stahle et al., 2009). However, the triple mutant fil-8 yab3-2 yab5-1 (yab135) and quadruple mutant fil-8 yab2-1 yab3-2 yab5-1 (yab1235) plants, hereafter referred to as
Figure 2. Redundancy of YABBY Gene Activity.

(A) to (C) YAB3 (yab3-2), YAB5 (pYAB5:GUS), and YAB2 (pYAB2:GUS) display unique gene expression patterns (9-d-old seedlings, top view).

(D) YAB3 is initially expressed throughout the leaf primordium (inset) but is switched off as the leaf differentiates. Note also the absence of expression in the petiole and midrib region.

(E) YAB5 expression is more widespread, with highest levels in the petiole and midrib region.

(F) YAB2 expression is restricted sharply to the petiole and midrib region.

(G) and (H) Cross sections reveal that at early stages, FIL and YAB3 expression is throughout the abaxial regions of leaves (arrowheads), but at later stages, FIL expression becomes localized to the margins (arrows).

(I) pYAB5:GUS is initially detected near vascular bundles and is later primarily in the central abaxial region of leaf primordia (arrow).

(J) Expression of pYAB2:GUS is limited to the abaxial midrib (arrow).

(K) to (N) Whole plant images of wild-type and YABBY multiple mutant plants.

(O) to (S) Inflorescence structure of wild-type and YABBY mutant plants. The transition from leaf (l) production to trichomeless bract-like (b) structures is...
YABBY triple and quadruple mutants, respectively, displayed a significant enhancement of the fil-8 yab3-2 double mutant phenotype (Figures 2K–2N): diminutive and bushy plants that lack apical dominance, and with all lateral organs displaying a dramatic loss of lamina expansion and polarity defects.

The leaves of YABBY triple and quadruple mutants develop in various shapes, ranging from organs with some lamina to fully radialized organs (Figures 2M, 2N, and 2Q–2S). An age-dependent gradient exists, such that the first few leaves have the greatest amount of lamina, whereas later produced leaves, especially the stem (cauline) leaves, tend to be radialized (Figures 2Q–2S). The flowers of YABBY triple and quadruple mutant plants consist almost entirely of single filamentous organs (Figures 2Q–2V). Occasionally, a filamentous organ subtends a solitary gynoecium composed of two carpels (Figure 2V), suggesting that some filamentous organs observed in the YABBY mutants (Figure 2P) represent the normally suppressed bracts of *Arabidopsis* flowers (Long and Barton, 2000), which are also occasionally initiated in *fil-8* single mutants. In both triple and quadruple mutants, the inflorescence meristem terminates in either a cluster of filaments (Figures 2Q, 2R, and 2V) or in carpeloid tissue with morphologically and anatomically normal ovules (data not shown). The presence of carpel tissue in the YABBY quadruple mutant is due to residual YABBY activity supplied by a functional CRC gene, since no evidence of carpel tissue was detected in the *crc-1 fil-8 yab2-1 yab3-2 yab5-1* pentuple mutant (Figures 2V and 2W).

**Polarity of YABBY Quadruple Mutant Leaves**

Our analyses of yabby mutant leaves were primarily focused on the first formed leaves, since SAM activity, which may affect polarity establishment in leaf primordia, is disrupted in YABBY mutants. In wild-type *Arabidopsis* plants, trichomes are limited to the adaxial surfaces of the first four to six leaves (Figure 3A), with later produced leaves having trichomes on both surfaces. The first few rosette leaves of YABBY quadruple mutants display trichomes exclusively on their adaxial surface, indicating that some adaxial–abaxial polarity exists (Figure 3E).

In wild-type leaves, the adaxial and abaxial epidermal surfaces are distinct, with the adaxial epidermis consisting of cells of relatively uniform size and sparsely interspersed stomata, while the abaxial epidermal cells are variably sized with a higher density of stomata (Figures 3C and 3D). Epidermal cells of YABBY quadruple mutant leaves are uniformly large compared with the wild type and are neither identical to wild-type adaxial nor wild-type abaxial cells (Figures 3E and 3F). Internally, the lamina of wild-type *Arabidopsis* leaves comprises six cell layers: the adaxial epidermis, a single adaxial layer of palisade mesophyll, three abaxial layers of spongy mesophyll, and the abaxial epidermis (Figure 3G). The dark green leaves of YABBY quadruple mutants are noticeably thicker than the wild type, with a total of 7 to 12 cell layers, usually lacking a clear spongy/palisade differentiation (Figure 3H). Occasionally, the adaxial-most subepidermal cell layer retains anatomical aspects of the palisade mesophyll, being slightly elongated perpendicular to the laminar surface and without large air spaces between the cells (Figures 3I to 3J). In radialized leaves, there is little to distinguish the different mesophyll layers (Figure 3K). In wild-type *Arabidopsis* leaves, the xylem is located adaxially and phloem abaxially (Figure 3I), but in bundles of YABBY quadruple mutant leaves that exhibit lamina growth, this polarity is usually skewed in orientation such that the arrangement of phloem and xylem is not perpendicular to the leaf axis (Figure 3J). In contrast, radialized leaves of quadruple mutants tend to have an amphi-ribral arrangement of vascular bundles, where central xylem tissue is surrounded by clusters of phloem (Figures 2T and 3K), an arrangement typically found in abaxialized radial leaves (Waites and Hudson, 1995).

**Expression of Polarity Markers in the YABBY Quadruple Mutant**

The *yab3-2* gene trap allele faithfully expresses GUS in the YAB3 expression domain and serves as a useful molecular marker of adaxial–abaxial polarity during lateral organ development (Kumaran et al., 2002). In YABBY triple and quadruple mutant backgrounds, GUS expression, although extremely weak compared with the wild type, is clearly abaxial (Figures 3L–3N). Even radialized organs retain this biochemical signature of polarity, although expression in older leaves may be expanded to the adaxial regions (Figure 3N; Stahle et al., 2009).

We examined global polar gene expression patterns in *fil yab3* and *fil yab3 yab5* mutants. We identified sets of polarly expressed genes, defined as genes modified in the adaxial (*phb-1d*) and the abaxial (*pANT>>KAN2*) genotypes relative to the wild type (Figure 3O; see Supplemental Data Set 1 online). Using the set of identified genes as a proxy for polar gene expression, YABBY mutants are neither clearly abaxialized nor adaxialized; rather, overall polar gene expression appears reduced. YABBY triple mutants display reduced expression of both adaxial (e.g., *PHB, REV, AS2*) and abaxial (e.g., *ARF4*) polarity markers (see Supplemental Table 1 online). These data are in agreement with the mixed morphological attributes of the mutant leaves.

**Lamina of the YABBY Mutants Have a Mixture of Leaf and Shoot Characters**

When the activities of two of the principal regulators of organ polarity, *PHB*-like HD-Zip genes and *KAN1*-like GARP family genes, are expanded throughout leaf primordia, polarity is not
established and lamina are not initiated (Eshed et al., 2001; McConnell et al., 2001). YABBY activity is greatly reduced in the apolar phb-1d primordia (Siegfried et al., 1999), but in YABBY quadruple mutant leaves, polarity is established but not maintained. Thus, a common theme to the miniature filamentous leaves of YABBY quadruple mutants and the apolar leaves of pANT>>KAN2 and phb-1d is a lack of lamina growth. To characterize the “YABBY-dependent” leaf programs, we examined global gene expression patterns in fil yab3 and YABBY triple mutant shoots. Overall, expression of 1190 genes (fold change > 2, false discovery rate P < 0.05) was altered in these apices, and attempts to find specific signatures in the form of enriched pathways among these genes failed. This failure may reflect the pleiotropic nature of the YABBY mutants that lack specific cell types such as stipules, are impaired in growth, and, as will be discussed below, have altered behavior of the SAM.

We took advantage of the other mutant backgrounds that, similar to the YABBY quadruple mutants, also lacked lamina. “Leaf lamina” genes were thus defined as genes downregulated in the three laminaless genotypes (phb-1d, pANT>>KAN2, and fil yab3 yab5; see Methods) relative to expression in the wild type (Figure 4A). These criteria were met by 587 lamina marker genes (see Supplemental Data Set 2 online). Looking for enriched gene families, we identified many cell cycle genes, including CYCB and CYCA families, histones, kinesins, and DNA replication genes, along with three members of the FAMA bHLH clade, previously reported to regulate stomata development (MacAlister et al., 2007). Notably, five CIN-TCP genes were found to be downregulated in all laminaless genotypes, and particular examination of this family showed that all eight CIN-TCP genes are downregulated to different degrees (Figure 4B). Indeed, many of the leaf lamina genes were also greatly downregulated in the 35S:
miR319b;35S:miR-3TCP genotype relative to the wild type (Figure 4A), suggesting that downstream factors of the Cin-Tcp pathway may not be activated in laminaless genotypes. Transcriptome analysis has previously identified gene expression patterns that reflect maturation and differentiation during leaf development, and these have been used to formulate a digital differentiation index (DDI) reflecting the developmental state of leaves (Efroni et al., 2008). When applied to evaluate the differentiation status of YABBY mutant leaves, the majority of gene expression is at a low DDI, reflecting a young stage of leaf differentiation, similar to the 35S:miR319b;35S:miR-3TCP genotype (Figure 4C). In contrast, adaxialized or abaxialized leaves exhibited a bimodal DDI, indicating that the young status of YABBY mutants is not simply due to a loss of lamina or a failure to maintain polarity.

Given that YABBY mutant leaves appear to be stunted at a young differentiated state, and that they do not appear to establish lamina-specific genetic programs, we examined whether SAM-specific genetic programs were properly downregulated. Since the quadruple YABBY mutant displays GUS activity (due to the presence of the yab3-2 allele), we utilized a transactivation line in which YABBY function has been reduced using a synthetic microRNA designed to target Fil and Yab3 (Moore et al., 1998; Alvarez et al., 2006). The transactivation line (pANT>>miR-YAB13) closely resembles the fil yab3 double mutant (Goldshmidt et al., 2008). Remarkably, the pWUS:GUS marker, which is normally only expressed in the central zone of the SAM (Mayer et al., 1998; Williams et al., 2005), is expressed at the adaxial tips of YABBY mutant leaves (Figure 4D). Expression of pWUS:GUS appears to be a reactivation, since neither younger pANT>>miR-YAB13 leaves nor primordia anlagen express the GUS marker. The domain of pWUS:GUS marker expression is also expanded in the pANT>>miR-YAB13 shoot apex relative to its expression in the wild type, consistent with previous observations demonstrating expansion of WUS expression in both inflorescences and flower meristems of YABBY mutants (Goldshmidt et al., 2008).

Leaf Margin Structure in YABBY Loss-of-Function Plants

While most leaves of YABBY triple and quadruple mutants lack lamina, the first formed leaves, although reduced in size, are
somewhat laminar, allowing comparisons with wild-type leaves. In the wild type, leaf margins are serrated with hydathodes differentiating at the tips of serrations. At the cellular level, conspicuous leaf margin cells mark the boundary between the adaxial and abaxial epidermises. These highly elongated cells are arranged in a continuous cell file along the perimeter of the leaf (Figures 5A and 5C). On the adaxial side, directly adjacent to the leaf margin cells, are two to three rows of small isodiametrically shaped epidermal cells (Figure 5E). YABBY mutant leaves lack the typical marginal elaborations that characterize wild-type leaves, such as serrations and hydathodes. Neither the specialized leaf margin cells nor the adjacent small adaxial cells are present in YABBY quadruple mutant leaves (Figures 5B, 5D, and 5F), irrespective of whether the mutant leaves exhibit laminar expansion or are fully radialized. Occasionally, isolated large cells are observed in the margins of quadruple leaves with some lamina expansion, but these resemble abaxial epidermal cells rather than typical marginal cells (Figure 5B). In addition, stipules, another marginal and lateral leaf structure (Nardmann et al., 2004), are also lacking in fil yab3, YABBY triple, and YABBY quadruple mutant leaves. Thus, all specialized marginal cell types do not form in YABBY mutants.

To investigate leaf margin establishment, we made use of an enhancer trap line (YJ158) that displays GUS activity in leaf margin cells (Eshed et al., 2004). In wild-type leaves, strong GUS expression is observed in a sharp and continuous marginal domain around the entire leaf margin (Figures 5G and 5I), while in pANT>>miR-YAB13 leaves, GUS activity was weak, patchy, and mostly distal (Figures 5H and 5J). Thus, the leaf margin, a domain that is derived from the establishment of leaf polarity, is missing from YABBY mutant leaves, even from those that are partially bifacial.

Venation and Auxin Patterning in YABBY Mutants

Since the leaf margin plays an important role in organizing movement of auxin during leaf development, in particular during vascular patterning and leaf serration formation, we investigated auxin dynamics in YABBY mutants. As a proxy for auxin maxima formation along the leaf margin, we first examined patterns of leaf venation. The venation patterns of YABBY mutant leaves are highly simplified compared with the normal reticulate patterns observed in wild-type Arabidopsis leaves (Figures 6A–6C). Leaves of YABBY double and quadruple mutants fail to form continuous loops of secondary veins. In radialized leaves of quadruple YABBY mutants, only a single central vascular strand differentiates.

We next analyzed the auxin response markers ATHB8 and DRS in wild-type and YABBY mutant leaves. The preprocambial marker, ATHB8, is one of the earliest markers of vasculature (Baima et al., 1995). ATHB8 expression in young leaf primordia was similar in both wild-type and pANT>>miR-YAB13 backgrounds (Figures 6E–6H). However, continuous loops of vasculature fail to form in YABBY mutants, and venation patterning is severely distorted (Figures 6I and 6J). DRS is a synthetic reporter composed of auxin-responsive elements transcriptionally fused with a reporter gene, GUS or green fluorescent protein (GFP; Ulmasov et al., 1999; Friml et al., 2003). In wild-type plants, an auxin response maximum is observed at the tips of young leaf

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Figure 5. Loss of YABBY Function Is Associated with a Loss of Leaf Margin Cells.

(A), (C), and (E) Wild-type margins are characterized by elongate marginal cells (e; red in [A] and [C]) and small isodiametric adaxial cells (s). (B), (D), and (F) yab1235 leaves lack these cell types, with occasional large cells (red in (B)) resembling large abaxial cells (see Figures 3C and 3D). (G) to (J) Marginal cell marker YJ158 is uniformly expressed in wild-type leaf marginal cells (G) and (I), and expression is patchy in pANT>>miR-YAB13 leaves (H) and (J). Bars = 100 μm.
Figure 6. Loss of YABBY Function Is Associated with Defects in Auxin Patterning.
primordia (Figure 6M). As leaf development proceeds, a DR5 maximum is maintained at the leaf tip and additional foci of DR5 expression are observed at hydathodes (Figures 6M and 6O, arrows). In pANT>>miR-YAB13 seedlings, DR5 expression is much weaker and fails to be strongly maintained (Figures 6L, 6N, and 6P). Hydathodes, with their corresponding points of DR5 expression, are not observed (Figure 6P). A weak DR5 response is consistent with overall lower levels of auxin and reduced PIN1-GFP expression (see below).

We examined pPIN1:PIN1-GFP expression during leaf development in YABBY quadruple mutants. PIN-FORMED1 (PIN1) encodes an auxin efflux carrier, and its localization on the plasma membrane is thought to indicate directional auxin flow (Benkova et al., 2003; Reinhardt et al., 2003). We utilized a translational fusion of PIN1 to GFP (pPIN1:PIN1-GFP; Heisler et al., 2005) to visualize PIN1 expression in YABBY quadruple mutants. During wild-type leaf development, PIN1-GFP is initially expressed uniformly in the primordium epidermis, where its apical polarity facilitates auxin transport distally (Scarpella et al., 2006). At this stage, a single primary PIN1 convergence point is located at the primordium tip, where the incipient midvein is positioned (Scarpella et al., 2006). Since YABBY quadruple mutants form a midvein, as expected, we observe epidermal PIN1-GFP expression in both leaf primordia and the incipient midvein (Figures 6V and 6W, third formed leaf). However, the initially strong PIN1-GFP expression in the midvein is not maintained and quickly fades below detectable levels (Figures 6V and 6W, compare the PIN1-GFP expression in the first and second formed leaves). In wild-type leaves, the continuous loops of secondary veins are patterned by transient “secondary” PIN1 convergence points occurring exclusively at leaf margins (Figures 6Q, 6R, and 6U; Scarpella et al., 2006). Continuous loops of PIN1-GFP expression are not observed in the YABBY quadruple mutant. Instead, we often observed additional PIN1-GFP convergence points at sites where ectopic bulges form on the primordium (Figures 6S, 6T, 6V, and 6W, arrows). These secondary PIN1 convergence points are broader than those formed in the wild type, with PIN1 expression not limited to the margins but extending in several cells of the epidermis on both “sides” of YABBY mutant leaves.

This stable PIN1-GFP convergence point funnels auxin downward to meet the existing vasculature and resembles auxin patterning at the primordium tip rather than auxin patterning associated with secondary vein formation. Thus, secondary PIN1 convergence points in YABBY mutant leaves resemble those formed at leaf initiation rather than marginal secondary PIN1 convergence points of wild-type leaves.

Loss of YABBY Gene Function Affects Embryo Development

The abnormal DR5 and PIN1 distribution in YABBY mutant shoots promoted further analyses of these markers in mutant embryos, where the gradual and slow development of simple shoot elements permits easier scoring of patterning events. Wild-type Arabidopsis seedlings have two round-shaped cotyledons of equal size that symmetrically flank the SAM. The origin of this bilateral symmetry can be traced back to the transition stage of embryogenesis, when cotyledons are initiated (Figure 7A). In contrast, cotyledons of YABBY double (fil yab3), triple, and quadruple mutants are small and narrow, with only a single vascular strand (Figures 7D, 7E, 7I, and 7M). Strikingly, YABBY triple and quadruple mutant seedlings often have extra, or sometimes split, cotyledons (Figures 7B and 7C). The extent of polycotylty in YABBY mutants is variable, both in terms of cotyledon number and degree of cotyledon separation. For example, some quadruple YABBY mutant seedlings display three or four cotyledons, while others display only partial extra cotyledons, ranging from slight bulges to deep lobes (see Supplemental Figure 2 online). The observed polycotylty phenotype is partially penetrant, with ~28% of triple mutants and 50% of quadruple mutant seedlings having extra cotyledons (Table 1).

Because auxin maxima are thought to promote cotyledon establishment, we followed PIN1-GFP localization and DR5 activity during YABBY mutant embryo development. PIN1 is required for initial positioning of cotyledon primordia in the embryo by facilitating the formation of two auxin maxima at the late globular stage of embryogenesis (Benkova et al., 2003; Reinhardt et al., 2003). In wild-type embryos, expression of PIN1-GFP marks the sites of cotyledon initiation, with two focal points
evident from the late globular stage through the heart stage of embryogenesis (Figures 7F and 7G). In YABBY quadruple mutant embryos, during the early heart stage, PIN1-GFP expression does not appear to resolve cleanly into two focal points but rather is expressed more broadly across apical regions of the embryo (Figures 7J and 7K). At the late heart stage of embryogenesis, focal points of PIN1-GFP expression are often evident at more than two sites (Figure 7L) corresponding to developing cotyledons (Figure 7M). Each cotyledon is associated with a focal point of DR5:GFP expression at its tip, consistent with a local accumulation of auxin (Figures 7T and 7U).

To examine the effect of prolonged and widespread PIN1 expression on cotyledon formation, we expressed PIN1 under the control of the FIL promoter in the quadruple YABBY mutant background and scored for polycotyly. The frequency of polycotyledonous seedlings increased from 57 to 90% (Table 1). An increased frequency of polycotyly was observed in multiple independent lines. In contrast, expression of the bacterial
YABBY gene expression helps to differentiate leaves and shoot identities. First, YABBY gene activity is required for most aspects of leaf development; however, as YABBY gene expression is initially limited to the abaxial regions of the leaf anlagen in both the wild type (Watanabe and Okada, 2003) and in YABBY loss-of-function mutants, initial polarity establishment does not appear to require YABBY activity (Figure 3). Instead, establishment or maintenance of leaf developmental processes after leaf primordium initiation are lacking in YABBY mutants. The failure to maintain normal leaf development following initiation results, directly, or more likely indirectly, in a failure to maintain polar gene expression patterns established earlier. Thus, loss of YABBY function is associated with loss of leaf polarity in general rather than simply abaxialization or adaxialization.

Second, YABBY activity is required to establish a leaf marginal domain (Figure 5). In YABBY mutant leaves, auxin convergences subsequent to leaf initiation appear to be planar rather than linear (Figure 6). One interpretation is that YABBY mutant leaves fail to establish normal laminar growth and that subsequently formed auxin maxima recapitulate the pattern normally found at the leaf initiation stage. In this scenario, the bulges formed on the flanks of YABBY mutant leaves represent aberrant “leaf primordia” induced by secondary auxin maxima, which in the wild type would mark the sites of secondary leaf veins and the establishment of reticulate venation. As a consequence, the failure to properly organize marginal leaf tissues, which are required for the development of the reticulate venation in wild-type leaves, results in highly simplified venation patterns in YABBY mutant leaves. The lack of all other marginal elaborations, such as serrations and hydathodes, and other specialized marginal cells promoting SAM maintenance and adaxial leaf differentiation (Alvarez and Smyth, 1999; Chen et al., 1999; Eshed et al., 1999, 2004; Sawa et al., 1999a, 1999b; Siegfried et al., 1999; Golz et al., 2004; Juarez et al., 2004; Goldshmidt et al., 2008; Stahle et al., 2009). The combination of autonomous and nonautonomous defects results in a mutant phenotype that is enigmatic, with nearly every aboveground shoot-derived organ affected. This is surprising considering that YABBY mRNAs and proteins are largely only expressed in the abaxial regions of developing leaves (Sawa et al., 1999a; Siegfried et al., 1999; Watanabe and Okada, 2003; Golz et al., 2004; Navarro et al., 2004). Furthermore, the whole plant YABBY mutant phenotype is in many respects more severe than either KANADI loss-of-function or PHB gain-of-function mutant phenotypes, despite YABBY gene expression being greatly reduced in these genetic backgrounds (McConnell and Barton, 1998; Siegfried et al., 1999; Eshed et al., 2004).

YABBY Genes Help to Differentiate Leaves from Shoots

In this study, we analyzed plants in which all vegetative YABBY activity is compromised. Members of the Arabidopsis YABBY gene family are functionally redundant, and differences in expression in older leaves or specific organs are consistent with partial subfunctionalization or neofunctionalization following gene duplications (Figure 2). Using morphology, anatomy, global gene expression patterns, and distribution of auxin-related markers, several lines of evidence lead us to propose that YABBY gene expression helps to differentiate leaf and shoot identities.

DISCUSSION

Since their discovery more than a decade ago, YABBY genes have been described as promoting abaxial leaf differentiation, lamina growth, floral organ identity, and as nonautonomously

<table>
<thead>
<tr>
<th>YABBY Mutant Genotype</th>
<th>No.</th>
<th>Percentage of Polycotyledonous Seedlings</th>
</tr>
</thead>
<tbody>
<tr>
<td>yab13 (double)</td>
<td>371</td>
<td>15</td>
</tr>
<tr>
<td>yab135 (triple)</td>
<td>340</td>
<td>28</td>
</tr>
<tr>
<td>yab1235 (quadraple)</td>
<td>426</td>
<td>50</td>
</tr>
<tr>
<td>yab1235 (quadraple);</td>
<td>213</td>
<td>96</td>
</tr>
<tr>
<td>pFIL::PIN1</td>
<td>135</td>
<td>84</td>
</tr>
<tr>
<td>yab1235 (quadraple);</td>
<td>200</td>
<td>32</td>
</tr>
</tbody>
</table>

auxin-metabolizing enzyme, iaaL, under the control of the FIL promoter in the quadruple YABBY mutant background, reduced the frequency of polycotyly to 32%. Thus, increasing PIN1-mediated auxin transport in the FIL expression domain results in a greater incidence of polycotyly in YABBY mutants, while increasing auxin conjugation has the opposite effect. No effect was observed in a wild-type background.

From the late heart stage, PIN1-GFP is conspicuous in the L1 of the wild-type SAM; however, this expression is reduced or not detected in quadruple YABBY mutant embryos (Figures 7H, 7I, 7L, and 7M). SAM gene expression was examined by following the expression of a pCLV3::GFP-ER marker during embryogenesis and establishment of the vegetative SAM. In wild-type embryos, pCLV3::GFP-ER is expressed in torpedo and later stage embryos demarcating the central zone of the SAM (Figures 7N and 7Q). In YABBY triple mutants, the expression domain of pCLV3::GFP-ER is expanded relative to that seen in the wild type (Figures 7O and 7R). In contrast, embryos in which YAB3 is ectopically expressed under the control of the AS1 promoter (which drives expression throughout lateral organs) exhibit arrest of the SAM (see Supplemental Figure 3 online) and reduction in the expression of pCLV3::GFP-ER (Figures 7P and 7S).

During seedling development of YABBY triple and quadruple mutants, the primary SAM (Figures 7V–7Z) is not maintained, and subsequent shoot growth is due to development from meristems at leaf axils or from ectopic meristems that develop on the adaxial side of the aberrant lamina (see Supplemental Figure 4 online). YABBY triple and quadruple mutant seedlings produce only two to four rosette leaves before the primary SAM terminates (Figures 7X–7Z). Leaves produced immediately prior to SAM termination are frequently radialized (Figure 7X). The wild-type SAM normally develops a tunica corpus structure characteristic of many angiosperms during the heart to torpedo stages of embryogenesis, and this is maintained throughout vegetative and reproductive development (Figure 7W; see Supplemental Figure 4 online). In histological sections of 10-d-old seedlings, the SAM of YABBY quadruple mutants is smaller than that of the wild type and with a less well-defined tunica corpus structure (Figure 7Z; see Supplemental Figure 4 online).
may be a downstream consequence of the loss of proper marginal auxin flow. It is of note that marginal structures lacking in YABBY mutants include both abaxial and adaxial cell types, implying non-cell-autonomous YABBY activity, consistent with their loss being a downstream event.

Third, YABBY mutants fail to initiate lamina genetic programs and fully repress SAM genetic programs. YABBY mutants fail to establish a "lamina gene expression program," characterized by expression of a class of TCP transcription factors that act to sculpt later leaf development (Nath et al., 2003; Palatnik et al., 2003; Ori et al., 2007; Efroni et al., 2008; Figure 4). Based on indices of maturation of differentiation, YABBY mutants are neither abaxial nor adaxial but remain in a state of differentiation that characterizes young leaves. Furthermore, plants with reduced YABBY activity fail to appropriately repress genes that are normally expressed only in Arabidopsis shoots from developing leaves. WUS is expressed at the adaxial tips of YABBY mutant leaves in a shoot-like manner, and class I KNOX genes are ectopically expressed in fil yab3 leaves (Kumaran et al., 2002). The increased thickness of YABBY mutant leaves relative to wild-type leaves (Figure 3) could be due to less focal auxin flow (see above) or, alternatively, ectopic expression of shoot meristem genes, or a combination of both processes.

YABBY proteins physically interact with LEUNIG, which is hypothesized to act as a transcriptional corepressor, raising the possibility that YABBY proteins may act to repress transcription of target genes (Navarro et al., 2004; Stahle et al., 2009). However, it is unlikely that YABBY proteins directly negatively regulate WUS, since it is adaxially expressed in YABBY mutant leaf tips and is temporally activated much later than the first phenotypic defects observed in YABBY mutant leaves (Figure 4).

Thus, its ectopic expression appears to be a nonautonomous downstream consequence of loss of YABBY activity.

Fourth, expression of a SAM factor (CLV3) that does not overlap in its expression domain with any of the YABBY gene products is altered, consistent with nonautonomous patterning defects of the central SAM region in fil-8 and fil-8 yab3-2 mutants (Goldshmidt et al., 2008). In addition, SAM PIN1 expression is reduced in YABBY mutant embryos, another nonautonomous defect possibly related to changes in auxin flow in the newly formed leaves. While causation is not proven, it is plausible that gene expression changes during embryogenesis in YABBY mutants ultimately lead to their SAM arrest during seedling growth.

Finally, polycotyly is another surprising phenotype, considering that YABBY genes are initially expressed in two discrete domains in the heart-stage embryo representing cotyledon primordia (Figure 7). Polycotyly can be viewed as a failure to establish the lamina development program in the cotyledons, with a reiteration of “primordium” auxin maxima in developing cotyledons resulting in the development of lobed or additional cotyledons. Increasing auxin mobility or synthesis in the YABBY expression domain facilitates the formation of additional auxin maxima, while iaaL expression reduces their frequency, presumably by decreasing active auxin levels. Since initial YABBY expression follows the establishment of auxin maxima, marking cotyledon establishment, YABBY activity acts to stabilize the bilateral symmetry, perhaps by activating lamina-specific programs, including establishment of the linear marginal auxin flow characteristic of leaves.

On the basis of these observations, we present here a hypothesis explaining why the seed plant–specific YABBY genes have become indispensable for most aspects of shoot growth in Arabidopsis. The numbers on the left correspond to the approximate leaf stages illustrated by the leaf primordium numbers on the petunia (Petunia hybrida) SAM, with green shading representing YABBY gene expression. During early stages (1 and 2), YABBY gene expression is activated abaxially in response to earlier acting polarity genes, and YABBY activity during these stages is required for proper signaling between leaf primordia and the SAM (Goldshmidt et al., 2008). YABBY-LEUNIG complexes likely act during these stages, since leunig mutations enhance SAM loss in a YABBY mutant background (Stahle et al., 2009). YABBY activity is required to limit auxin flows to lateral margins (stages 2 and 3), thus influencing leaf margin growth and differentiation and, consequently, reticulate vascularization of the leaf. YABBY activity is also required to initiate leaf-specific genetic programs, such as that defined by CIN-TCP genes, which lead to subsequent events in leaf differentiation (stages 3 and 4).
flowering plants. The complex YABBY mutant phenotype can be interpreted as a failure to establish a laminar growth pattern (e.g., TCP maturation/determination program), with leaves developing with a mixture of shoot-like characteristics (shoot-like PIN1 expression and ectopic WUS expression) and YABBY-independent leaf characteristics. The further observation that loss of YABBY function leads to altered SAM gene expression indicates that YABBY genes alter meristem behavior from a distance, perhaps serving to modify the shoot to accommodate the development of leaves by signaling to the SAM that a group of cells has been recruited into leaf formation. Without YABBY activity, neither the leaf nor the SAM continues to develop normally, making YABBY genes important regulators integrating growth and development of the entire shoot in Arabidopsis (Figure 8).

YABBY Genes and the Evolution of the Seed Plant Leaf

While most developmental genetic studies of angiosperm shoots categorized genes as either leaf genes or meristem genes, it is becoming clear that most angiosperm leaves and SAMs share similar developmental genetic programs (Brand et al., 2007; Efroni et al., 2010; Floyd and Bowman, 2010). For example, PIN-mediated auxin transport is required for serration and leaflet development in leaves as well as for the initiation of leaves in the SAM peripheral zone (Benkova et al., 2003; Reinhardt et al., 2003; Hay and Tsiantis, 2006; Barkoulas et al., 2008; Koenig et al., 2009; Kawamura et al., 2010). CUP-SHAPED COTYLEDON (CUC) gene expression marks boundaries at the periphery of the SAM and boundaries between elaborations at the margins of leaves (Aida et al., 1999; Nikovics et al., 2006; Blein et al., 2008; Berger et al., 2009), and class I KNOX expression is required for SAM maintenance and promotes leaflet growth in species with complex leaves (Barton and Poethig, 1993; Long et al., 1996; Hay and Tsiantis, 2006; Barkoulas et al., 2008). Both CUC and class I KNOX genes have expression patterns that correlate with auxin flow and presumed auxin maxima, with both marking sites of auxin minima in the SAM and leaf (Furutani et al., 2004; Heisler et al., 2005; Hay et al., 2006; Barkoulas et al., 2008; Blein et al., 2008). Likewise, WOX-related gene expression is required for maintenance of growth of the SAM (WUS) and leaf margins (PRESSED FLOWER, WOX7; Laux et al., 1996; Mayer et al., 1998; Vendebussche et al., 2009). However, there are exceptions to the shared genetic programs, with ARP (in many angiosperms), JAGGED, and YABBY gene expression restricted to leaves (Waite et al., 1998; Sawa et al., 1999a; Siegfried et al., 1999; Timmermans et al., 1999; Tsiantis et al., 1999; Watanabe and Okada, 2003; Dinneny et al., 2004; Ohno et al., 2004).

One hypothesis is that the common genetic programs in the SAM and leaf are due to homology (Floyd and Bowman, 2010). Seed plant leaves evolved from ancestral lateral branch systems. Thus, the leaf was evolutionarily transformed from an indeterminate radial structure to one that is determinate, dorsiventral, and laminar (Zimmerman, 1952; Stewart and Rothwell, 1993; Beerling and Fleming, 2007; Sanders and Rothwell, 2009). In this scenario, the genetic programs in the leaf would be derived from genetic programs present in the ancestral lateral branches (Floyd and Bowman, 2010). Because the origin of the YABBY gene family maps to the last common ancestor of extant seed plants (Figure 1) and YABBY genes are required for laminar growth, it has been proposed that YABBY genes may have been involved in the origin and evolution of seed plant leaves (Floyd and Bowman, 2006, 2010). The failure to establish marginal leaf domains, to initiate lamina programs, and to maintain leaf polarity, the failure of suppression of SAM genetic programs, and the patterns of auxin flow in YABBY mutants provide further compelling support for this hypothesis.

The earliest seed plants bore leaves that were still in many respects stem-like and were only laminar at ultimate branches of highly ramified structures (Serbet and Rothwell, 1992; Stewart and Rothwell, 1993; Beerling and Fleming, 2007; Sanders and Rothwell, 2009), very unlike the leaves of Arabidopsis (with simple laminar development). In fact, the leaves of all extant seed plants are clearly distinct as lateral organs from their inception on the SAM. Although there are no data available on gene expression patterns of gymnosperm YABBY genes, this suggests that YABBY genes may function in gymnosperms as they do in Arabidopsis. Evolutionary developmental changes to produce the leaf of extant seed plants occurred not all at once but gradually through time, with a trend toward an earlier manifestation of dorsiventral and laminar development (Floyd and Bowman, 2010). As the YABBY genes appear to map to the origin of seed plants, the function of YABBY genes may also have expanded gradually, integrating and differentiating leaf and stem development. Data for YABBY genes in gymnosperms and additional angiosperm species are needed to more accurately assess the ancestral role of YABBY genes for angiosperms and to confirm or reject the hypothesis that YABBY genes integrate leaf and stem development in all extant seed plants. The YABBY gene family is an intriguing and likely candidate for a gene family whose origin and evolution were partially responsible for seed plant leaves.

METHODS

**yab2-1 and yab5-1**

Cleaved-amplified polymorphic sequence PCR markers were designed to identify Arabidopsis thaliana yab2-1 and yab5-1 alleles. For yab2-1, the ethyl methanesulfonate–induced mutation creates a PacI site. Primers flanking the PacI site amplify a 410-bp product. Digestion yields 190- and 220-bp products. For yab5-1, a partial EcoRI site (lacking the 3′ C) was designed at the 3′ end of a 40-bp primer used to amplify a 112-bp product. Upon EcoRI digestion, the wild-type allele (C) yields two fragments of 40- and 72-bp product, whereas the mutant allele (T) does not contain an EcoRI restriction site. Primers for genotyping yab2-1 are Ya2-F (5′-TGCGTCCATTGCGACGATG-3′) and Ya2-R (5′-ATTAA-TTCTGACATCGTG-3′). Primers for genotyping yab5-1 are Yab5-5 (5′-ATTGTGTTATTTAATAAAGGAGGGAACT-3′) and Yab5-R (5′-TCTACATTGATGGAGCCACATTCT-3′).

**Multiple Mutants**

yab2-1 yab5-1 plants were generated by crossing homozygous yab2-1 and yab5-1 lines; double mutants were selected in the F2 by PCR
screening, fil-8 yab3-2 yab5-1 plants were crossed to yab5-1 plants to generate fil-8 yab3-2 yab5-1 triple mutants. F2 plants exhibiting novel phenotypes were genotyped by PCR to confirm homozygosity for all three mutant alleles. fil-8/+ yab3-2 yab5-1 plants were crossed to yab2-1 plants to generate quadruple mutants and genotyped in a similar manner. crc-1 plants were crossed to fil-8/+ yab3-2 yab2-1 yab5-1 plants. In the F2 generation, crc-1 plants were tested for GUS (the yab3-2 allele is a Ds insertion allele exhibiting GUS staining). GUS-positive lines were further genotyped by PCR for yab2-1, yab5-1, and fil-8. A plant of genotype fil-8/+ yab3-2 yab2-1 yab5-1 crc-1 was obtained and maintained to produce the pentuple mutant. Plants were grown in long days, with 18 h of light at 22 °C. Since triple and quadruple YABBY mutants are sterile, the F1, F2, and F3 transgenics were introgressed into a fil-8/yab235 background. DR5:GFP, ATHB8:GUS, and PIN1:PIN1-GFP were crossed into the pANT>>miR-YAB13 background, and individuals harboring all three transgenes were selected in the F1.

Transactivation of Ectopic and Reporter Gene Expression

Ectopic and reporter gene expression was accomplished using the transactivation system of Moore et al. (1998). In this system, a driver transgene, such as pAS1:LhG4, produces a chimeric transcription factor in a defined expression pattern that can act as a transcriptional activator of a reporter gene. The transactivation cassette was introduced into a fil-8/yab235 background, DR5:GFP, ATHB8:GUS, and PIN1:PIN1-GFP were crossed into the pANT>>miR-YAB13 background, and individuals harboring all three transgenes were selected in the F1.

Histology and Microscopy

Scanning electron microscopy was performed as described previously (Alvarez et al., 1992; Siegfried et al., 1999). GUS staining was performed according to the methods described by McConnell and Barton (1998). General histology was performed as described by Emery et al. (2003). For whole-mount analyses of embryos, developing seeds were excised from developing gynoecia with 27-gauge needles, cleared overnight in Hoyer’s solution (Liu and Meinke, 1998), and observed as described by Izhaki and Bowman (2007).

To image fluorescent signals, young seedlings (3–4 d old) were carefully removed from Murashige and Skoog plates, dissected, and mounted in water between a glass slide and a cover slip as described previously (Marcos and Berleth, 2009). Imaging was performed using a Leica TCS SP5 inverted confocal laser-scanning microscope. Excitation was at 488 nm (25% of laser output). The collection wavelengths were 505 to 525 nm for GFP and 600 to 670 nm for plastid autofluorescence. Scanning speed was set at 400 Hz and 512 × 512 pixel frames. The pinhole was set at 1.7 airy units. The objective was a 63.0×, 1.20-numerical aperture Leica HCX PL APO CS water-immersion lens. Image analysis was performed using Imaris 5.7 software (Bitplane). The GFP signal was false colored green, and the chlorophyll signal was false colored red.

Tissue Collection, RNA Preparation, and Microarray Hybridization

Plants were grown for 14 d under short-day conditions. Tissue collection, using microscissors, of the different samples always took place at the same daily time interval (1–3 h after the beginning of the light period). In all experiments, two independent biological replicates were sampled. Total RNA (7 to 10 μg) was extracted with the RNeasy RNA isolation kit (Qiagen). Labeled complementary RNA was prepared and hybridized to Affymetrix ATH1 GeneChips according to the manufacturer’s guidelines (Affymetrix).

Bioinformatic Analysis

To identify differentially expressed genes in yabby mutants, RNA was extracted from apices (leaves 1 and 2 and cotyledons removed) of short-day-grown, 14-d after sowing seedlings of the wild type (four repeats) and mutants (two repeats), using the Qiagen RNEasy kit and hybridized to ATH1 Affymetrix expression arrays according to the manufacturer’s recommendation. Signal values were obtained and normalized using the GeneChip-Robust Multi-array Analysis protocol. Genes with expression values lower than log2(10) were removed. All analysis was done with R 2.7.2 (www.r-project.org) and Bioconductor 2.2 (www.bioconductor.org). False discovery rate correction was done using the multtest package of R.

To compare the expression of polarity-related genes in yabby mutants with polarity mutants, previously published data of 14-DAS apices (ALP, AYL, Efroni et al., 2008; phb-1d, pANT>>KAN2) (Malitsky et al., 2008), along with ATH1 Affymetrix expression data of two repeats of similar-age apices of fil-8 yab3-2, fil-8 yab3-2 yab5-1, and kan1 kan2 plants, were processed using MAST, median normalized to 50, and their average was used for comparison. Genes with expression values below 30 in all samples were discarded from further analysis.

To define polarity genes, a 1.5-fold change cutoff was used, and a gene list was defined by the following criterion: phb-1d greater than wild type and wild type greater than pANT>>KAN2 or pANT>>KAN greater than wild type and wild type greater than phb-1d. Dividing by the maximal expression value detected among mutant apices was used to normalize each gene’s expression level. A polarity index was calculated as average expression of abaxial genes (pANT>>KAN2 is greater than wild type) minus the average expression of adaxial genes (phb-1d is greater than wild type). Lamina genes were defined as reduced in all phb-1d, pANT>>KAN2, and fil yab35 compared with the wild type. Data for the TCP octuple mutant were published previously together with the DDI scripts (Efroni et al., 2008).

Accession Numbers

The Arabidopsis Genome Initiative locus identifiers for CRC, FIL, YAB2, YAB3, YAB5, and INO correspond to AtNG1g69110, AtNG2g45190, AtNG1g08465, AtNG4g00180, AtNG2g26580, and AtNG1g23420, respectively. Microarray data have been deposited in the Gene Expression Omnibus database, series number GSE21705.

Supplemental Data

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

**Supplemental Figure 1.** The YABBY Gene Family.

**Supplemental Figure 2.** Polycotyl in YABBY Quadruple Mutants.

**Supplemental Figure 3.** Effects of YABBY Activity on Vegetative Shoots.

**Supplemental Figure 4.** YABBY Mutants Fail to Maintain a Functional SAM, and Continued Growth Arises from Auxillary and de Novo–Initiated Meristems.

**Supplemental Table 1.** Expression of Organ Polarity Markers in Selected Apices.

**Supplemental Data Set 1.** Genes Modified in Their Expression in yabby Triple Mutant Apices.

**Supplemental Data Set 2.** Genes Modified in Their Expression in Mutants Lacking Lamina Expansion.

**Supplemental Data Set 3.** Text File of Alignment Corresponding to the Phylogeny in Supplemental Figure 1 Online.

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REFERENCES


