

# Model for the regulation of *Arabidopsis thaliana* leaf margin development

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Biological shapes are often produced by the iterative generation of repeated units. The mechanistic basis of such iteration is an area of intense investigation. Leaf development in the model plant *Arabidopsis* is one such example where the repeated generation of leaf margin protrusions, termed serrations, is a key feature of final shape. However, the regulatory logic underlying this process is unclear. Here, we use a combination of developmental genetics and computational modeling to show that serration development is the morphological read-out of a spatially distributed regulatory mechanism, which creates interspersed activity peaks of the growth-promoting hormone auxin and the CUP-SHAPED COTYLEDON2 (CUC2) transcription factor. This mechanism operates at the growing leaf margin via a regulatory module consisting of two feedback loops working in concert. The first loop relates the transport of auxin to its own distribution, via polar membrane localization of the PINFORMED1 (PIN1) efflux transporter. This loop captures the potential of auxin to generate self-organizing patterns in diverse developmental contexts. In the second loop, CUC2 promotes the generation of PIN1-dependent auxin activity maxima while auxin represses CUC2 expression. This CUC2-dependent loop regulates activity of the conserved auxin efflux module in leaf margins to generate stable serration patterns. Conceptualizing leaf margin development via this mechanism also helps to explain how other developmental regulators influence leaf shape.

Leaf margin morphology is commonly used to distinguish different plant species and often evolves in close correspondence with the environment. For example, the degree of leaf serration is a good predictor of mean annual temperature of landmasses over geological timescales (1). Variations in margin morphology were first documented in antiquity (2) and were among the first heritable traits studied in plants (3). Nonetheless, a predictive model of leaf margin shape acquisition is lacking. Recent genetic analyses have revealed two key processes required for serration formation: regulated auxin transport by the efflux carrier PINFORMED1 (PIN1) (4) and activity of the growth repressor CUP-SHAPED COTYLEDON2 (CUC2), which is negatively regulated by miR164 (5). PIN1 has a polar subcellular localization and forms convergence points at the margins of leaves, creating localized auxin activity maxima that are required for the outgrowth of serrations (4, 6). Leaves of both *pin1* and *cuc2* mutants fail to initiate serrations and have smooth margins, highlighting the importance of these gene products for leaf morphogenesis (4, 5). Here, we show how CUC2 activity and auxin transport and signaling are regulated and integrated to sculpt leaf margin serrations.

## Results

**Interspersed CUC2 and Auxin Activity Maxima Underpin Serration Formation.** To understand the dynamics of CUC2 and auxin activity during serration development, we monitored *CUC2::CUC2:VENUS* expression and the auxin response sensor *DR5::GFP*. Before serration outgrowth, *DR5::GFP* is restricted to the leaf tip and absent from the leaf margin, whereas *CUC2::CUC2:VENUS* is expressed

along the margin (Fig. 1*A*). A focus of *DR5::GFP* expression then emerges at a site of serration initiation, which correlates with repression of *CUC2::CUC2:VENUS* (Fig. 1*B*). As the leaf margin grows, subsequent auxin activity foci appear in a basipetal sequence at positions where *CUC2::CUC2:VENUS* expression is lost and further serrations form (Fig. 1*C*). We, therefore, hypothesized that this interspersed distribution of auxin activity maxima and CUC2 expression at the leaf margin underpins serration development. We tested this hypothesis by abolishing this interspersed pattern and examining the impact on serration formation. First, we created a continuous marginal domain of CUC2 expression using an *AtMLI::CUC2:VENUS* transgene to express CUC2 throughout the epidermis (Fig. 1*D–G* and Fig. S1*A–D*) (7). Second, we applied auxin exogenously to create a continuous distribution of auxin (Fig. 1*H* and *I*). Both treatments yielded leaves with smooth margins, suggesting that continuous CUC2 or auxin activity is sufficient to prevent serration formation. Epidermal expression of CUC2 caused additional defects, including leaves with fewer or aberrantly positioned serrations and cup-shaped cotyledons similar to those observed in *cuc1*; *cuc2* double mutants (Fig. 1*J* and *K*). These defects further highlight the significance of discontinuities in CUC2 expression for proper CUC function during development.

**CUC2 and Auxin Activity Maxima Are Regulated in a Feedback Loop via PIN1.** To investigate the regulatory relationship between CUC2 and PIN1 during serration development, we analyzed auxin activity and PIN1 localization in *cuc2* leaf margins. In contrast to wild type, *DR5::GFP* expression foci are absent along the margin during early leaf development in *cuc2* mutants and are present only at the leaf tip (Fig. 2*A* and *B*, 500- $\mu$ m leaf length). This expression becomes diffuse around the margins of *cuc2* leaves later in development (Fig. 2*C–F*, 750- $\mu$ m leaf length, see ref. 8) and resembles the expression of *DR5* in response to auxin transport inhibition (4). This pattern of auxin activity is associated with a lack of PIN1 convergence points in the *cuc2* margin (Fig. 2*G* and *H* and Fig. S1*E* and *F*). However, PIN1 localization remains polar in each cell. Therefore, CUC2 is re-

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the operation of a feedback loop that is critical for serration development. Within this loop, CUC2 promotes the establishment of PIN1 convergence points that generate auxin maxima, which in turn repress CUC2 expression. These interactions generate a pattern of auxin maxima interspersed with CUC2 expression along the leaf margin.

**Epidermal PIN1 Activity Is Sufficient to Regulate Morphogenetic Events in the Leaf.** To test whether PIN1 activity in the epidermis alone is sufficient for serration development, we expressed *AtML1::PIN1:GFP* in *pin1* mutants. We observed that epidermal expression of *AtML1::PIN1:GFP* can restore serration formation in these leaves (Fig. 4 A–G and Fig. S2 A–E). PIN1 convergence points in the leaf epidermis not only are required for serration patterning, but also mark sites where auxin is transported to internal tissue layers and guides the development of vasculature (4, 6). We found that normal vascular patterning was restored upon PIN1:GFP expression in the epidermis of *pin1* mutants (Table 1 and Fig. S2 F–J). The development of vasculature in the absence of PIN1 activity in internal tissue layers of the leaf may reflect the compensatory action of other PIN protein family members acting redundantly in these tissues. These results indicate that PIN1 activity in the epidermis of the leaf margin underlies both serration and vascular development. To investigate whether these two processes can be uncoupled, we analyzed leaf vasculature in *cuc2* mutants. Although they lack serrations, epidermal PIN1 convergence points, and discrete peaks of auxin activity, *cuc2* leaves mirror wild-type vascular development in secondary vein number, the capacity of veins to branch to the

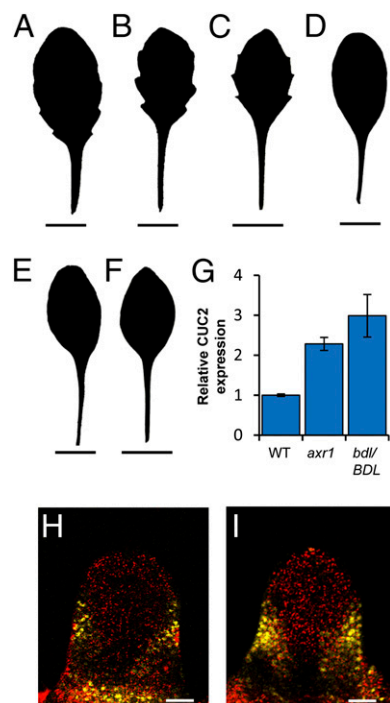
**Table 1. *AtML1::PIN1:GFP* rescues vascular defects in *pin1-7* mutants**

Genotype	Average no. of secondary veins in fifth rosette leaf ( $\pm$ SE)
Col	9.76 $\pm$ 0.16
<i>pin1-7</i>	12.8 $\pm$ 1.16
<i>AtML1::PIN1:GFP</i>	9.71 $\pm$ 0.30
<i>pin1-7; AtML1::PIN1:GFP</i>	10.38 $\pm$ 0.26

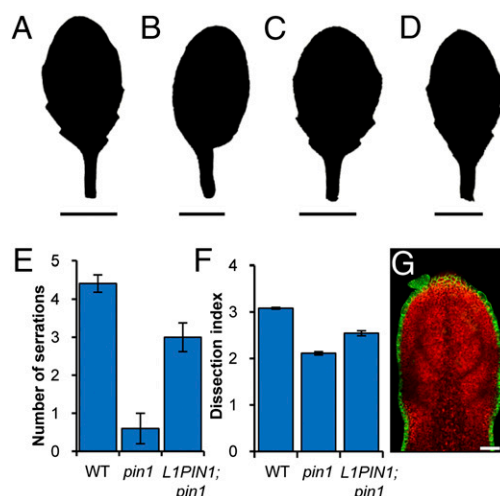
ANOVA *P* value <0.001 for all genotypes differing from *pin1-7*. *n* = 15.

quinternary order, and the ontogeny of *ATHB-8::GUS* vascular marker expression; except that secondary veins do not terminate at the margins of *cuc2* leaves (Table 2 and Fig. S3 A–F). Thus, vasculature can, but serrations cannot, form in the absence of epidermal PIN1 convergence points in *cuc2* mutants. These observations indicate considerable modularity in leaf morphogenetic pathways, despite the use of epidermal auxin maxima as a shared patterning cue in wild-type leaves.

The functional importance of interspersed CUC2 and auxin activity maxima at the leaf margin, together with previous studies (9), suggests the following conceptual model of serration development (Fig. 5A). At the heart of the model is a feedback loop between auxin transport by PIN1 (process 1 in Fig. 5A) and polar localization of PIN1 by auxin (process 2). Within each cell, PIN1 is polarized toward the neighboring cell with a higher auxin concentration (up-the-gradient polarization model) (10, 11). Operation of this mechanism requires the presence of CUC2, which enables the reorientation of PIN1 (process 3). Auxin, in turn, represses CUC2 expression (process 4), which yields an interspersed pattern of auxin convergence points and CUC2 activity. In *Arabidopsis* leaves, which grow primarily at the base, this mechanism produces a basipetally progressing sequence of auxin convergence points separated by CUC2 expression. This pattern controls local rates of margin outgrowth, yielding serra-



**Fig. 3. Auxin regulates leaf margin development via repression of CUC2.** (A–F) Silhouettes of fifth rosette leaf are shown for all genotypes. The auxin signaling mutants *axr1-3* (B) and *bdll/BDL* (C) have more serrated leaf margins than wild type (A). *axr1-3; cuc2-3* (D) and *bdll/BDL; cuc2-3* (E) double mutants mimic the smooth leaf margins of *cuc2-3* (F). (G) Quantitative RT-PCR analysis showed that *axr1-3* and *bdll/BDL* plants displayed elevated CUC2 gene expression compared with wild type. (H and I) Confocal micrographs showing CUC2::CUC2::VENUS expression (yellow) in fifth rosette leaf 125  $\mu$ m in length in wild type (H) and *axr1-3* (I). (Scale bars: A–F, 1 cm; H and I, 25  $\mu$ m.) Error bars represent SE of mean from three biological replicates.



**Fig. 4. Epidermal PIN1 activity is sufficient for serration development.** (A–D) Silhouette of fifth rosette leaf in wild type (A), *pin1-7* (B), *AtML1::PIN1:GFP* (C), and *pin1-7; AtML1::PIN1:GFP* (D). (E) Quantification of serration number in fifth rosette leaf of wild type, *pin1-7*, and *pin1-7; AtML1::PIN1:GFP* (*L1PIN1; pin1*). (F) Quantification of margin shape using the dissection index (perimeter squared)/(4 $\pi$   $\times$  area) in fifth rosette leaf of wild type, *pin1-7*, and *L1::PIN1:GFP; pin1-7* (*L1PIN1; pin1*). (G) Confocal micrograph of single optical section showing *AtML1::PIN1:GFP* expression (green) in fifth rosette leaf 250  $\mu$ m in length. (Scale bars: A–D, 1 cm; G, 25  $\mu$ m.) Error bars represent SE of mean. *n* = 20.



proximal edge is further enhanced by the assumed gradient of growth rates, decreasing away from the leaf base.

To further validate the model, we simulated the effect of several pharmacological and genetic manipulations and found that they recapitulate our biological observations (Fig. 5 *I–M*). To simulate *pin1* mutants, we set PIN1 concentration in all cells to 0. Auxin concentration then forms a continuous gradient from the leaf base to the tip (Fig. 5*I* and Movie S2). The diffuse concentration of auxin irreversibly represses *CUC2* expression outside the leaf base (Eq. S5). In the absence of the pattern of interleaved auxin concentration and *CUC2* expression maxima, no serration is formed (compare with Fig. S3 *J–L*). Similar model behavior corresponds to simulated N-1-naphthylphthalamic acid (NPA) treatment of the leaf, in which polar auxin transport (parameter *T* in Eq. S2) is set to 0. Serrations are also absent when exogenous auxin application is simulated by assuming a constant supply of auxin to each cell (parameter  $\Phi_{\text{ext}}$  in Eq. S1). High auxin concentrations repress *CUC2* expression outside the leaf base (Eq. S5), which prevents repolarization of PIN1 (Eq. S4). Consequently, neither *CUC2* expression nor auxin convergence points form (Fig. 5*J* and Movie S3).

To further investigate the role of *CUC2* in serration formation, we simulated *cuc2* mutant leaves by setting *CUC2* expression to 0 after the PIN1 convergence point at the leaf tip had formed (Fig. 5*K* and Movie S4), as this convergence point is maintained in *cuc2* leaves (Fig. 2*B*). The simulated *cuc2* mutant leaves have a smooth margin due to the lack of indentations marked by *CUC2* expression and the lack of protrusions marked by PIN1 convergence points (compare with Fig. S3 *M–O*). These convergence points do not form as PIN1 fails to repolarize in the absence of *CUC2*. The *cuc2* mutant simulation also captured the dynamic pattern of auxin activity observed during *cuc2* leaf margin development, where a continuous auxin gradient gradually emerges between the minimum at the leaf base and the maximum at the tip. In contrast to these genotypes that lack serrations, leaves with elevated *CUC2* expression have more pronounced serrations, as illustrated by the *mir164a*, *axr1*, and *bdl/BDL* mutants (compare with Fig. S3 *P–X*). We simulated increased *CUC2* expression by increasing maximum *CUC2* concentration (parameter  $CUC_{\text{max}}$  in Eq. S5). As anticipated, the resulting model had deeper serrations (Fig. 5*L* and Movie S5). To investigate the significance of discontinuous *CUC2* expression we simulated uniform *CUC2* expression in each cell. The simulated leaves had reduced depth and number of serrations (Fig. 5*M* and Movie S6). Models in which a random variation of auxin production (“noise”) was introduced to investigate the robustness of the patterning mechanism further illuminated the role of *CUC2* (Fig. S5 *A–H*). In the case of uniform *CUC2* expression, auxin maxima moved along the margin. For a moderate amplitude of noise this motion was sporadic, resulting in irregular, asymmetric leaf shapes (Fig. S5 *A–C*). At higher amplitudes the position of maxima changed frequently, and the lack of sustained maxima resulted in no visible serrations being formed (Fig. S5*D*). In contrast, the model of a wild-type leaf, which has interspersed *CUC* expression, showed no departure from the deterministic model for moderate noise and approximately correct serrations for high amplitude of noise (Fig. S5 *E* and *F*). The feedback between *CUC2* and polar auxin transport is thus essential for the robust formation of serration patterns.

## Discussion

Our data indicate that correct PIN1 polarization at the leaf margin requires the presence of *CUC2*. However, computational models suggest that a feedback between PIN polarization and auxin transport alone can produce periodic patterns of PIN convergence points (10, 11), which raises the question of the precise morphogenetic role of *CUC2*. Our model of leaf margin development suggests that the spatially discontinuous expression of *CUC2* has two functions. First, as PIN1 repolarization requires the presence of *CUC2*, localized down-regulation of *CUC2* by auxin stabilizes the position of PIN1 convergence points and auxin maxima on the

margin (Fig. S5 *A–H* and Movies S7, S9, S10, and S11). Second, *CUC2*-dependent growth repression marks the position of indentations. Thus, *CUC2* is essential to robustly position protrusions and indentations of individual serrations. In the future it will be essential to scrutinize assumptions of the model at the molecular level and understand the molecular events that cause PIN1 proteins to localize against the auxin activity gradient. In this context it will also be important to determine the mechanistic basis through which *CUC2* influences PIN1 polarization and whether *CUC2* also provides PIN1-independent input into cell polarization and tissue patterning. PID family proteins, previously shown to affect PIN1 localization (13), may play a role in these processes.

The positioning of lateral organs at the shoot apex is another process regulated by PIN1 and *CUC* proteins (14), suggesting that *CUC2* may also stabilize PIN1 convergence points during organogenesis. Extending our model to the epidermal layer of the shoot apex may, therefore, improve our understanding of phyllotactic pattern formation by eliminating heuristic assumptions required to properly position and maintain PIN1 convergence points in earlier models (11). The assumption that phyllotaxis can be modeled at the level of the epidermis (10, 11) is further supported by the observation that PIN1 expression, restricted to the epidermis, restores organogenesis and fertility in *pin1* mutants (Fig. S2 *K–R*).

The proposed model also sheds light on leaf development in other *Arabidopsis* mutants and transgenic plants. For example, leaves with reduced TCP activity have an increased number of serrations (15, 16). According to our model, this increase is a direct consequence of the increased margin length, which creates additional space for serrations to form via *CUC2*, PIN1, and auxin activity. Experimental data support this idea as increased serration of leaves with reduced TCP activity is partially suppressed in a *pin1* or *cuc2* mutant background (Fig. S6 *A–F*). The repression of *CUC2* by auxin at the leaf margin, shown here, also clarifies the nature of genetic interactions between the *asymmetric leaves1* (*as1*) and *axr1* mutants (4). Specifically, deeply lobed leaf margins form in *as1;axr1* double mutants, where *CUC2* expression is elevated as a consequence of reduced auxin signaling, but not in *as1* mutants alone (Fig. S6 *G–I*). This enhancement of *as1* reflects *CUC2*-dependent activation of the *KNOX* (*knotted1*-like homeobox) gene *BREVIPEDICELLUS* (*BP*) in the sinus regions of the leaf margin (Fig. S6 *J–O*). *CUC2*, PIN1, *KNOX*, and TCP proteins are also required for compound leaf development where the margin produces individual leaflets of varied shapes and arrangement (17–24). Extending the framework we propose here to other taxa should thus help to elucidate the molecular mechanisms that underlie the diversity of leaf forms.

In conclusion, serration formation captures two key elements of the broader logic of development. First, morphogenetic information is imparted by discontinuous sequential expression of developmental regulators. Second, temporal periodicity depends on spatial patterning mechanisms that maintain approximately equidistant boundaries of morphogenetically active molecules within developing structures. Such boundaries can be generated by different mechanisms, such as reaction–diffusion, gradient-based positional information, and active auxin transport (which is unique to plants) (25). Our results indicate that growth provides a crucial input to these diverse, independently evolved patterning processes that generate periodic structures and provide a framework for conceptualizing this input.

## Materials and Methods

All alleles and transgenic lines (Table S4) were grown on soil under long-day conditions; genetic methods and methods for plasmid construction, analysis of transgenics, treatments using indole-3-acetic acid (IAA) and 2,4-dichlorophenoxyacetic acid (2,4-D), quantitative RT-PCR, leaf clearings, obtaining silhouettes, and quantifying leaf margin shape can be found in *SI Materials and Methods*. Scanning electron microscopy and confocal



microscopy were performed as previously described (26). GUS staining was performed as previously described (7). Models were implemented using the L-system-based modeling software L-studio (<http://algorithmicbotany.org/lstudio>). A detailed model description can be found in **SI Materials and Methods**. The source code for the models is available on request.

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