LEAF MORPHOGENESIS IN DICOTYLEDONS: CURRENT ISSUES

Nancy G. Dengler[1],* and Hirokazu Tsukaya†

*Department of Botany, University of Toronto, Toronto, Ontario M5S 1A1, Canada; and †National Institute for Basic Biology (Center for Integrated Bioscience, Okazaki Research Institutes), Okazaki 444-8585, Japan, and Form and Function, PRESTO, Japan Science and Technology Corporation, 4-1-8 Honcho, Kawaguchi 332-0012, Japan

The last decade of the twentieth century has witnessed a period of renewed interest, redefinition of questions, and some dramatic advances toward resolving some of the long-standing issues related to the developmental regulation of leaf morphogenesis. New interest has been sparked by the application of developmental genetics, molecular biology, and mosaic analysis to the study of genetic model species. The integration of knowledge gained from these these newer approaches with that derived from more than a century of comparative developmental morphology is crucial for advancing understanding of leaf morphogenesis. This link is particularly important for the interpretation of mutant phenotypes and gene expression patterns. In this brief review article, we provide a general framework for the study of leaf morphogenesis and identify areas where we believe that important issues remain unresolved.

Keywords: leaf development, symmetry, leaf initiation, expansion, primary morphogenesis, secondary morphogenesis.

Introduction

A major source of diversity in flowering plant form is a striking variation in leaf shape and size. Leaves vary from those having a simple blade with entire, serrate, or lobed margins to those having compound blades with pinnately or palmately arranged leaflets and, in some species, secondary and tertiary levels of segmentation. Not only does leaf shape vary dramatically among taxonomic groups, but individual leaves on the same plant may display quite different forms. Most plants express some degree of heteroblasty in which the shapes of leaves on an individual shoot vary with position. In some groups of plants, changes in environmental conditions induce a switch in leaf shape, a phenomenon known as environmentally induced heterophylly. This great variation in form, as well as its developmental basis, has intrigued botanists for over 150 yr.

The last decade of the twentieth century has witnessed a period of renewed interest, redefinition of questions, and some dramatic advances toward answering some of the long-standing questions about development of leaf form. New interest has been sparked by the application of developmental genetics and molecular biology to the study of genetic model species, such as *Arabidopsis thaliana*, *Antirrhinum majus*, and *Zea mays*, as well as other species known for a range of leaf shape mutants, such as *Lycopersicon esculentum* and *Pisum sativum*. Developmental investigations of these species have addressed major issues in leaf morphogenesis, such as the regulation of leaf initiation, the acquisition of leaf symmetry, the elaboration of leaf shape, the definition of leaf subregions, and the rela-

tionship between whole-organ development and events at the cellular level.

Our goals in this brief review article are to give an overview of leaf morphogenesis in dicotyledons and to identify the major unresolved issues of the developmental biology underlying the great diversity of mature dicot leaf form. The impetus to write this review came from organizing a symposium on leaf morphogenesis at the Sixteenth International Botanical Congress (1999). In this article, we emphasize issues discussed at that meeting; other perspectives are provided in a number of recent reviews of leaf morphogenesis (Cusset 1986; Dale 1988, 1992; Freeling 1992; Smith and Hake 1992; Tsukaya 1995; Hagemann and Gleissberg 1996; Sylvester et al. 1996; Poethig 1997; Brutnell and Langdale 1998; Tsiantis and Langdale 1998; Van Lijsebettens and Clarke 1998; Dengler 1999; Goliber et al. 1999; Sinha 1999; Van Volkenburgh 1999).

Leaf Attributes

Despite the great variation in mature shape, all leaves are thought to share a number of defining attributes: (1) a lateral position on the stem; (2) a determinate growth pattern; (3) association with an axillary bud on the adaxial side of the leaf base; (4) possession of subregions along the longitudinal leaf axis, usually represented by blade, petiole, and leaf base (and stipules, if present); and (5) dorsiventral symmetry with flattening in the transverse plane (fig. 1A, 1B). In addition, leaves develop in an environment where two additional polarities are imposed by the morphology of the shoot system as a whole. These are the longitudinal polarity of the shoot axis and the polarity of the phyllotactic system; the latter is particularly likely to influence leaf morphogenesis in species with helical phyllotaxis (fig. 1C; Tsukaya 1998).

While the five features listed above are generally accepted as diagnostic, interpretation of each is not always straight-

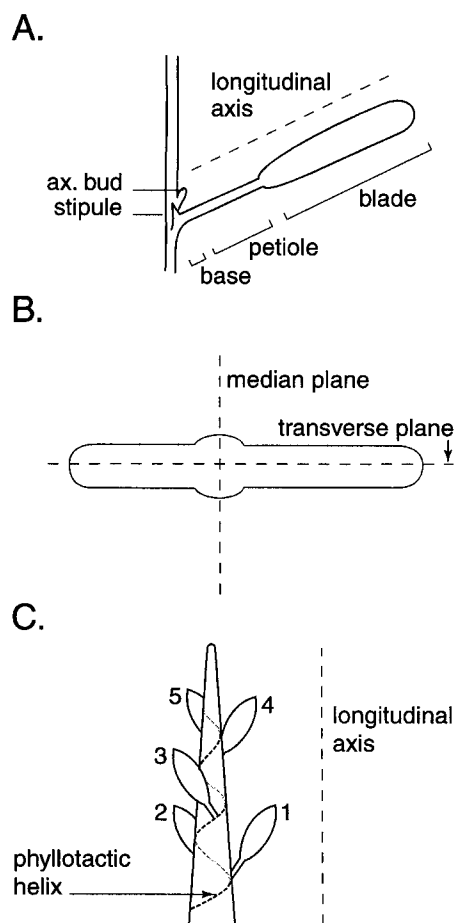[1] Author for correspondence; e-mail dengler@botany.utoronto.ca.

Fig. 1 Leaf symmetry and regions. *A*, Subdivision of leaf into blade, petiole, and leaf base regions along axis of longitudinal symmetry, giving proximo-distal symmetry. *B*, Leaf transsectional symmetry in the medial plane (dorsiventral symmetry) and in the transverse plane (centromedial asymmetry). *C*, Shoot polarities that influence leaf symmetry are the longitudinal polarity of the shoot axis and polarity related to helical phyllotaxis.

forward. For example, in certain plant taxa and mutants, leaves may appear to arise *de novo* on the surface of other leaves (Dickinson 1978; Barton and Poethig 1993). Definitive evidence that such leaves arise without the mediation of a shoot apical meristem is lacking, but these observations invoke questions about the role of the shoot apical meristem in the formation and determination of leaf identity. While dorsiventral symmetry characterizes leaves from inception in all cases that have been critically studied, all or some portions of mature leaves in many taxa are radially symmetrical. How this initial symmetry becomes either accentuated or lost during development is still unknown, at least at a molecular level (Kaplan 2001).

Similarly, while leaves are typically determinate, those of the genera *Guarea* and *Chisocheton* (Meliaceae) retain prolonged apical development, in which the leaf tip may continue to produce new leaflet primordia for more than 4 yr (Steingraeber and Fisher 1986; Fisher and Rutishauser 1990). Prolonged leaf growth also occurs in the genera *Monophyllaea* and *Strepto-*

carpus (Gesneriaceae; Jong and Burtt 1975; Cronk and Moller 1997; Tsukaya 1997). In these unusual species, the entire shoot system consists of a single cotyledon bearing epiphyllous inflorescences. The basal meristem of the cotyledon remains active throughout the life of the plant, producing new blade tissue and additional inflorescences. Although these developmental patterns are very unusual, such observations raise questions about the nature and regulation of the more typical determinate growth pattern. Thus, while the unifying general properties of leaves hold generally, unusual natural variants and, increasingly, mutations affecting these properties are being used to study their developmental regulation.

Phases of Leaf Morphogenesis

The process of leaf morphogenesis encompasses all aspects of the generation of leaf form from inception to maturity. Subdivision of this continuous process into separate phases has been conceptually useful for studying various aspects of leaf development (Jeune 1983; Jeune and LaCroix 1993; Poethig 1997). Here, we define three phases: (1) initiation, (2) primary morphogenesis, and (3) expansion and secondary morphogenesis (fig. 2). Each of the first three phases makes a unique contribution to the genesis of mature leaf form, but they also mesh together to provide a well-integrated developmental whole. We believe that it is useful to consider them separately since some contradictory results may arise simply from making observations on different phases of development.

Leaf Initiation

The regulation of leaf initiation (and its spatial pattern, phyllotaxis) is still one of the great unanswered questions of plant developmental biology. Although studies of leaf morphogenesis often focus on the postinitiation phases of leaf development, many aspects of leaf morphology arise at the time of leaf inception. For instance, the extent of the leaf initiation zone around the circumference of the apical meristem strongly influences the morphology of the leaf base (fig. 2*A*). Mutations that disrupt the process of initiation can have a dramatic impact on mature leaf form (Scanlon et al. 1996; Timmermans et al. 1998). The earliest known molecular marker of leaf initiation is the downregulation of class 1 homeobox (*KNOX*) genes, such as *Knotted-1* in *Zea mays* (Jackson et al. 1994) and *KNAT1* and *KNAT2* in *Arabidopsis* (Lincoln et al. 1994). These homeobox genes are reported to be negatively regulated by the *ASSYMMETRIC1*, *ASYMMETRIC2*, and *SERRATE* genes in leaf primordia of *Arabidopsis* (Bryne et al. 2000; Ori et al. 2000; Semiarti et al. 2001). Details of the regulation of *KNOX* gene expression in the shoot apical meristem and leaf primordia are still unclear but, when known, will provide insight into the mechanism of establishment of a distinct identity for leaf primordia.

One intriguing hypothesis about the mechanism of leaf initiation is that it may be partly or wholly controlled by physical factors. Observations of localized changes in the orientation of cortical microtubules and cellulose microfibrils in regions of the shoot apical meristem have indicated that leaf primordia arise simply in response to the mechanical buckling of the meristem surface, allowing a new axis of growth (Green 1999).
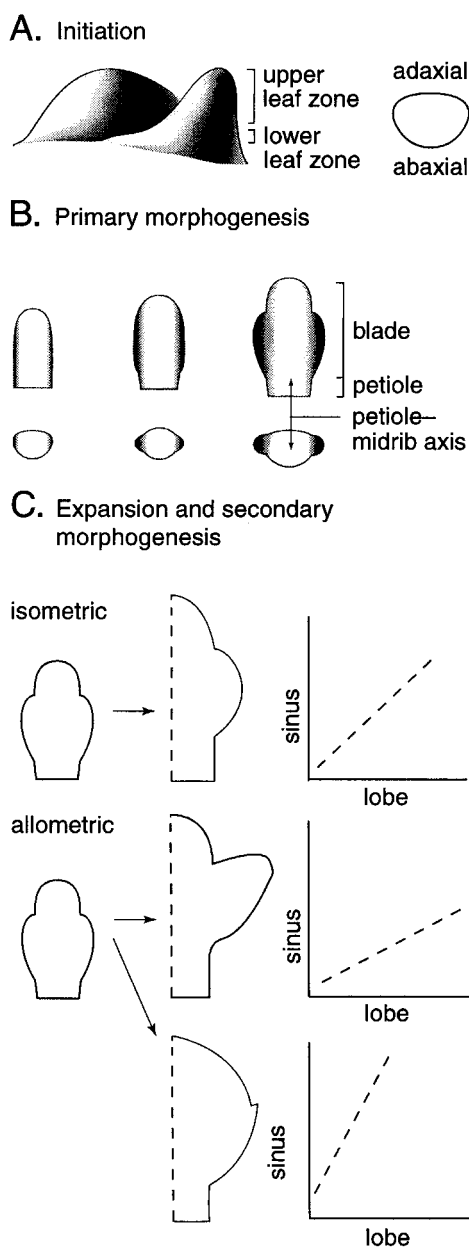
A. Initiation

upper leaf zone
lower leaf zone
adaxial
abaxial

B. Primary morphogenesis

blade
petiole
petiole–midrib axis

C. Expansion and secondary morphogenesis

isometric

sinus / lobe

allometric

sinus / lobe

sinus / lobe

Fig. 2 Three phases of leaf morphogenesis. *A*, Leaf initiation. Leaf primordium expresses longitudinal symmetry (upper and lower leaf zones) and dorsiventral symmetry (differences between adaxial and abaxial sides). *B*, Primary morphogenesis. Marginal blastozone (stippled) expresses morphogenetic potential to form blade, lobes, and leaflets. Top row, adaxial view of leaf; bottom row, blade transverse sectional view. *C*, Expansion and secondary morphogenesis. Top, isometric expansion; bottom, allometric expansion of lobes and sinuses produced during primary morphogenesis.

Direct support for this idea has been provided by experiments in which the application of expansin protein to the shoot apical meristem resulted in leaf primordium-like outgrowths (Fleming et al. 1997, 1999). It is possible that such physical changes have a direct role in the downregulation of *KNOX* genes and in the initial expression of others. Leaf initiation can by in-

duced by the local application of auxin on otherwise leafless shoot apical meristems (Reinhardt 2000). Auxin can also induce localized growth (Cleland 1995) and gene expression (Guilfoyle et al. 1998). Knowledge of the interplay among physical factors, hormones, gene expression, and growth processes will be crucial for understanding the mechanisms and regulation of leaf initiation, as well as for later stages of morphogenesis.

Primary Morphogenesis

The term "primary morphogenesis" is used to describe developmental processes that establish the basic form of the leaf and, in doing so, determine both leaf symmetry and the major subregions of the leaf (Hagemann and Gleissberg 1996). In dicots, initiation of the lamina region is one of the earliest expressions of primary morphogenesis (fig. 2*B*). Initiation of a lamina at the primordium periphery typically coincides with the thickening growth of the petiole-midrib axis, delimiting the lamina and midrib domains within the distal portion of the leaf. At the same time, the longitudinal extent of lamina formation distinguishes the distal blade from the proximal petiole and leaf base regions. Although development of the blade is a fundamental property of primary morphogenesis in almost all dicot leaves, the mechanisms and their spatial and temporal regulation is poorly understood.

Currently, much attention has focused on the relationship between blade formation and the expression of dorsiventral symmetry. Extreme phenotypes of *phantastica* mutants in *Antirrhinum* have radially symmetrical leaves in which tissues normally found on the adaxial side of the leaf are missing or are ectopically expressed (Waites and Hudson 1995; Waites et al. 1998). A complementary phenotype has been described for the *phabulosa-1d* mutant of *Arabidopsis* in which leaves are also radialized, but abaxial tissues appear to be absent or misplaced (McConnell and Barton 1998). These genotypes have been hypothesized to reflect a requirement for expression of both adaxial and abaxial identity factors for the continued development of dorsiventral symmetry. Waites and Hudson (1995) further postulated that juxtaposition of expression domains of adaxial and abaxial genes is required for the alteration of growth direction that results in blade formation in wild-type leaves. This is an intriguing idea that requires further experimental and genetic testing. Thus far, recognition of adaxial and abaxial morphological domains has relied on using cell and tissue traits as markers of morphological identity (Waites and Hudson 1995; McConnell and Barton 1998). At present, the developmental coupling between morphological and histological characteristics is not well understood (Kaplan 2001). Recent observations on the expression pattern of genes, such as the *YABBY* family of transcriptional regulators, may help link the development of morphological symmetry with tissue and cell-specific traits (Siegfried et al. 1999; Bowman 2000). These genes are expressed solely in the abaxial half of the leaf primordium, indicating that they could regulate the patterns of tissue development specific to that side of the leaf.

Regardless of the molecular mechanisms by which the leaf blade is formed and dorsiventrality regulated, the strip of tissue at the margin of the primordium is part of the leaf that possesses morphogenetic potential (fig. 2*B*). This region has been

termed the "marginal blastozone" in order to emphasize its role in morphogenesis and to avoid the histogenetic implications of the term "marginal meristem" (Hagemann 1970; Hagemann and Gleissberg 1996). In simple leaves with entire margins, the marginal blastozone is active for a very short time, as indicated by cellular markers such as cell enlargement and the differentiation of trichomes (Hagemann and Gleissberg 1996; Donnelly et al. 1999). In leaves with more complex shapes, localized enhancement and suppression of growth results in the formation of leaflets, lobes, and marginal serrations (fig. 2B). Variation in both the relative position and timing of blastozone activity and of leaf primordium elongation can result in a great diversity of leaf shapes (Hagemann 1970; Jeune and LaCroix 1993; Gleissberg 1998a, 1998b; Gleissberg and Kadereit 1999).

Prolonged blastozone activity is associated with the formation of compound (i.e., dissected) leaves (DeMason and Villani 2001; Kaplan 2001; Kessler et al. 2001). In Lycopersicon, the delayed termination of meristematic activity has been shown to be correlated with a high level of expression of KNOX genes both at sites of leaf initiation and within developing leaves (Hareven et al. 1996; Chen et al. 1997). Furthermore, overexpression of KNOX genes in Lycopersicon promote branching during leaf development, resulting in highly ramified leaf forms (Hareven et al. 1996; Chen et al. 1997; Janssen et al. 1998). Together these results strongly implicate KNOX genes in compound leaf primary morphogenesis, at least in Lycopersicon. In Pisum, UNIFOLIA, a homolog of the floral meristem identity genes FLORICAULA and LEAFY, appears to play a similar role (Hofer et al. 1997; Gourlay et al. 2000; DeMason and Villani 2001).

The process of primary morphogenesis requires regional control over growth enhancement and suppression. Mature morphology, the differing developmental pathways followed by different regions of a developing leaf, and the genetic interactions among genes affecting leaf form all have supported the idea that the leaf is subdivided into distinct domains along its longitudinal and transverse axes (Gourlay et al. 2000; Kessler et al. 2001). For instance, in Pisum, the AFILA gene appears to interact with UNIFOLIA to produce leaflets in a proximal domain, while both AFILA and TENDRILLESS interact with UNIFOLIA to produce tendrils in a distal domain (Gourlay et al. 2000). In Lycopersicon, Kessler et al. (2001) found morphological and anatomical evidence for a marginal domain that appeared to be deleted in wiry mutants. In addition, the expression patterns of the YABBY genes provide evidence for abaxial and adaxial domains within Arabidopsis leaf primordia (Siegfried et al. 1999; Bowman 2000). The concept of domains and criteria for recognition of developmentally important domains is in need of critical evaluation; nevertheless, this term has been a useful one, both for describing the different behaviors of regions within developing leaves and for the interpretation of mutant phenotypes.

Expansion and Secondary Morphogenesis

Primary morphogenesis occurs during very young stages when the leaf is still protected by older leaves at the shoot apex. The third phase of leaf morphogenesis, expansion and secondary leaf morphogenesis, encompasses a much longer time period and represents an increase in surface area and volume of several thousandfold (Dale 1988). The pattern of expansion may be either isometric or allometric and may either retain or alter the shape established by primary morphogenesis (fig. 2C). For example, in Begonia dregei, differences in the sizes of leaf lobes and marginal teeth are established during the primary morphogenetic phase and are then maintained by isometric growth (McLellan and Dengler 1995). Allometric expansion, the more common growth pattern, is the basis of secondary morphogenesis. For instance, differences in lobe shape between subspecies of Curcurbita argyrosperma only appear during the expansion phase, well after the primary morphogenetic phases of growth (Jones 1993). In Gossypium barbardense, lobe shape differences between genotypes appear during primary morphogenesis but are greatly enhanced during allometric expansion (Dolan and Poethig 1991).

The correlation between leaf shape and the patterns of cell division and enlargement has long been a focus of research on leaf morphogenesis (Ashby 1948). As many as 95% of all leaf cells are formed during the expansion phase, and cell divisions may continue until the leaf reaches 90% of its final size (Dale 1976). For example, in Lycopus europaeus, both the initial formation (primary morphogenesis) and extension (secondary morphogenesis) of leaf lobes are associated with altered planes of cell divisions within the lobe (Jeune 1983). Such linkages can be interpreted as either that (1) the altered plane of cell divisions causes lobe formation or that (2) lobe formation results from a dramatic change in division plane. Careful experimentation will be required to distinguish between these alternatives. Likewise, the mutant phenotypes of the ROTUNDIFOLIA3 and ANGUSTIFOLIA genes of Arabidopsis thaliana illustrate a close association between the polarity of individual cell expansion and the leaf expansion phase of morphogenesis (Tsuge et al. 1996; Kim et al. 1998, 1999). ROTUNDIFOLIA3 mutants have short, rounded leaves, and the defect in leaf elongation is reflected in a suppression of cell enlargement along the longitudinal axis. In contrast, the ANGUSTIFOLIA mutant displays reduced growth in the transverse plane, resulting in long, narrow leaves. Like ROTUNDIFOLIA3, the leaf shape defect is also expressed in the axis of expansion of individual leaf cells.

The nature of the association between cell division, cell expansion, and overall leaf morphogenesis is still controversial (Kaplan 1992, 2001; Smith 1996; Marcotrigiano 2001). Certainly a number of studies indicate that leaf morphogenesis can compensate for perturbations in the normal course of cell proliferation and cell enlargement (Haber 1962; Hemerly et al. 1995; Traas et al. 1995; Smith et al. 1996; Mizukami and Fischer 2000). In these experimentally or genetically manipulated leaves, shapes are usually similar to wild type despite defects in cell division, but sizes are smaller, indicating a role for cell proliferation in providing the raw material for normal growth and in histogenetic events (Donnelly et al. 1999).

One distinctive feature of leaf development is the formation of internal layers through the predominantly anticlinal orientation of cell divisions within the leaf blade during the expansion and secondary morphogenesis phase (Maksymowych and Wochok 1969). As cell proliferation ceases, each tissue layer undergoes a characteristic pattern of histogenesis. Signaling between layers and cell types is also likely required for

normal cell differentiation (Brutnell and Langdale 1998). During normal leaf morphogenesis and histogenesis, growth of tissue layers must be coordinated to prevent buckling and curling. Recent experiments using graft chimeras between different genotypes or between species of contrasting leaf shapes have indicated that tissue layers differ in their influence on leaf shape (Dolan and Poethig 1998; McHale and Marcotrigiano 1998; Marcotrigiano 2001). Graft chimeras also demonstrate that, while regions of genetically distinct tissue play out their own developmental programs, there is a striking degree of coordination among tissues and regions of the leaf (Marcotrigiano 2001). These observations serve to highlight questions about the relationship between whole-organ morphogenesis and developmental events at the cellular and tissue levels.

Conclusions

Recent research in diverse areas, from comparative morphology to developmental genetics and molecular biology, has led to the definition of the major unresolved questions about the mechanisms and regulation of leaf morphogenesis. We regard the most significant of these as follows: (1) What regulates the formation of a leaf primordium from the shoot apical meristem? (2) How does leaf growth become determinate and what is the significance of expression of meristem-specific genes within the leaf primordium? (3) How are regional domains along the longitudinal axis (leaf base, petiole, and blade), the medial plane (adaxial and abaxial regions), and the transverse plane (right and left leaf halves) delimited from each other and their differential development regulated? (4) During primary morphogenesis, how are spatial and temporal patterns of growth suppression and enhancement regulated? (5) What is the relationship between regulation at the whole-organ or regional level and regulation of cellular events, including the differential influence of tissue layers? Observations gained over the last decade have contributed at least partial answers to some of these questions but, more importantly, have served to define and focus interest on them. Ten years from now, we expect to have more complete answers and a better understanding of their universality.

Acknowledgments

Literature Cited

Ashby E 1948 Studies in the morphogenesis of leaves. I. An essay on leaf shape. New Phytol 47:153–176.

Barton MK, RS Poethig 1993 Formation of the shoot apical meristem in *Arabidopsis thaliana*: an analysis of development in the wild-type and in the shoot meristemless mutant. Development 119:823–831.

Bowman JL 2000 The YABBY gene family and abaxial cell fate. Curr Opin Plant Biol 3:17–22.

Brutnell TP, JA Langdale 1998 Signals in leaf development. Adv Bot Res 28:162–195.

Bryne ME, R Barley, M Curtis, JM Arroyo, M Dunham, A Hudson, RA Martienssen 2000 *Asymmetric leaves1* mediates leaf patterning and stem cell function in *Arabidopsis*. Nature 408:967–971.

Chen J-J, B-J Janssen, A Williams, N Sinha 1997 A gene fusion at a homeobox locus: alterations in leaf shape and implications for morphological evolution. Plant Cell 9:1289–1304.

Cleland RE 1995 Auxin and cell elongation. Pages 214–227 in PJ Davies, ed. Plant hormones and their role in plant growth and development. Kluwer, Dordrecht.

Cronk Q, M Moller 1997 Strange morphogenesis: organ determination in *Monophyllaea*. Trends Plant Sci 2:327–328.

Cusset G 1986 La morphogenese du limbe des Dicotyledones. Can J Bot 64:2807–2839.

Dale JE 1976 Cell division in leaves. Pages 315–345 in MM Yeoman, ed. Cell division in higher plants. Academic Press, New York.

——— 1988 The control of leaf expansion. Annu Rev Plant Physiol Plant Mol Biol 39:267–295.

——— 1992 How do leaves grow? BioScience 42:423–432.

DeMason DA, PJ Villani 2001 Genetic control of leaf development in pea (*Pisum sativum*). Int J Plant Sci 162:493–511.

Dengler NG 1999 Anisophylly and dorsiventral shoot symmetry. Int J Plant Sci 160(suppl):S67–S80.

Dickinson TA 1978 Epiphylly in angiosperms. Bot Rev 44:181–232.

Dolan L, RS Poethig 1998 The *Okra* leaf shape mutation in cotton is active in all cell layers of the leaf. Am J Bot 85:322–327.

Donnelly PM, D Bonetta, H Tsukaya, R Dengler, NG Dengler 1999 Cell cycling and cell enlargement in developing leaves of *Arabidopsis*. Dev Biol 215:407–419.

Fisher JB, R Rutishauser 1990 Leaves and epiphyllous shoots in *Chisocheton* (Meliaceae): a continuum of woody leaf and stem axes. Can J Bot 68:2316–2328.

Fleming AJ, D Caderas, E Wehrli, S McQuenn-Mason, C Kuhlemeier 1999 Analysis of expansin-induced morphogenesis on the apical meristem of tomato. Planta 208:166–174.

Fleming AJ, S McQueen-Mason, T Mandel, C Kuhlemeier 1997 Induction of leaf primordia by the cell wall protein expansin. Science 276:1415–1418.

Freeling M 1992 A conceptual framework for maize leaf development. Dev Biol 153:44–58.

Gleissberg S 1998a Comparative analysis of leaf shape development in Papaveraceae-Chelidonioideae. Flora 193:387–409.

——— 1998b Comparative analysis of leaf shape development in Papaveraceae-Papaveroideae. Flora 193:269–301.

Gleissberg S, JW Kadereit 1999 Evolution of leaf morphogenesis: evidence from developmental and phylogenetic data in Papaveraceae. Int J Plant Sci 160:787–794.

Goliber T, S Kessler, J-J Chen, G Bharathan, N Sinha 1999 Genetic, molecular, and morphological analysis of compound leaf development. Curr Topics Dev Biol 43:259–290.

Gourlay CW, JMI Hofer, THN Ellis 2000 Pea compound leaf architecture is regulated by interactions among the genes *UNIFOLIATA*, *COCHLEATA*, *AFILA*, and *TENDRIL-LESS*. Plant Cell 12:1279–1294.

Green PB 1999 Expression of pattern in plants: combining molecular and calculus-based biophysical paradigms. Am J Bot 86:1059–1076.

Guilfoyle T, G Hagen, T Ulmasov, J Murfett 1998 How does auxin turn on genes? Plant Physiol 118:341–347.

Haber AH 1962 Nonessentiality of concurrent cell divisions for degree of polarization of leaf growth. I. Studies with radiation induced mitotic inhibition. Am J Bot 49:583–589.

Hagemann W 1970 Studien zur Entwicklungsgeschichte der Angio-

spermenblatter: ein Beitrag zur Klarung ihres Gestaltungsprinzips. Bot Jahrb 90:297–413.

Hagemann W, S Gleissberg 1996 Organogenetic capacity of leaves: the significance of marginal blastozones in angiosperms. Plant Syst Evol 199:121–152.

Hareven D, T Gutfinger, A Parnis, Y Eshed, E Lifschitz 1996 The making of a compound leaf: genetic manipulation of leaf architecture in tomato. Cell 84:735–744.

Hemerly A, J de Almeida Engler, C Bergounioux, M Van Montagu, G Engler, D Inze, P Ferreira 1995 Dominant negative mutants of the Cdc2 kinase gene uncouple cell division from iterative plant development. EMBO (Eur Mol Biol Organ) J 145:3925–3936.

Hofer J, L Turner, R Hellens, M Ambrose, P Matthews, A Michael, N Ellis 1997 *UNIFOLIATA* regulates leaf and flower morphogenesis in pea. Curr Biol 7:581–587.

Jackson D, B Veit, S Hake 1994 Expression maize *KNOTTED1*-related homeobox genes in the shoot apical meristem predicts patterns of morphogenesis in the vegetative shoot. Development 120:405–413.

Janssen B-J, L Lund, N Sinha 1998 Overexpression of a homeobox gene, *LeT6*, reveals indeterminate features in the tomato compound leaf. Plant Physiol 117:771–786.

Jeune B 1983 Croissance des feuilles de *Lycopus europaeus* L. Beitr Biol Pflanzen 58:253–266.

Jeune B, CR LaCroix 1993 A quantitative model of leaflet initiation illustrated by *Murraya paniculata* (Rutaceae). Can J Bot 71:457–465.

Jones CS 1993 Heterochrony and heteroblastic leaf development in two subspecies of *Cucurbita argyrosperma* (Cucurbitaceae). Am J Bot 80:778–793.

Jong K, BL Burtt 1975 The evolution of morphological novelty exemplified in the growth patterns of some Gesneriaceae. New Phytol 75:297–311.

Kaplan DR 1992 The relationship of cells to organism in plants: problems and implications of an organismal perspective. Int J Plant Sci 153(suppl):S28–S37.

——— 2001 Fundamental concepts of leaf morphology and morphogenesis: a contribution to the interpretation of molecular genetic mutants. Int J Plant Sci 162:465–474.

Kessler S, M Kim, T Pham, N Weber, N Sinha 2001 Mutations altering leaf development in tomato. Int J Plant Sci 162:475–492.

Kim G-T, H Tsukaya, H Uchimiya 1998 The *ROTUNDIFOLIA3* gene of *Arabidopsis thaliana* encodes a new member of the cytochrome P-450 family that is required for the regulated polar elongation of leaf cells. Genes Dev 12:2381–2391.

——— 1999 Changes in the shapes of leaves and flowers upon overexpression cytochrome P450 in *Arabidopsis*. Proc Natl Acad Sci USA 96:9433–9437.

Lincoln C, J Long, J Yamaguchi, K Serikawa, S Hake 1994 A *Knotted1*-like homeobox gene in *Arabidopsis* is expressed in the vegetative meristems and dramatically alters leaf morphology when overexpressed in transgenic plants. Plant Cell 6:1859–1876.

Maksymowych R, ZS Wochok 1969 Activity of marginal and plate meristem during leaf development of *Xanthium pennsylvanicum*. Am J Bot 56:26–30.

Marcotrigiano M 2001 Genetic mosaics and the analysis of leaf development. Int J Plant Sci 162:513–525.

McConnell JR, MK Barton 1998 Leaf polarity and meristem formation in *Arabidopsis*. Development 125:2935–2942.

McHale N, M Marcotrigiano 1998 *LAM1* is required for dorsoventrality and lateral growth of the leaf blade in *Nicotiana*. Development 125:4235–4243.

McLellan T, NG Dengler 1995 Pattern and form in repeated elements in the development of simple leaves of *Begonia dregei*. Int J Plant Sci 156:581–589.

Mizukami Y, RL Fischer 2000 Plant organ size control: *AINTEGUMENTA* regulates growth and cell numbers during organogenesis. Proc Natl Acad Sci USA 97:942–947.

Ori N, Y Eshed, G Church, JL Bowman, S Hake 2000 Mechanisms that control *knox* gene expression in the *Arabidopsis* shoot. Development 127:5523–5532.

Poethig RS 1997 Leaf morphogenesis in flowering plants. Plant Cell 9:1077–1087.

Reinhardt D, T Mandel, C Kuhlemeier 2000 Auxin regulates the initiation and radial position of plant lateral organs. Plant Cell 12:507–518.

Scanlon MJ, RG Schneeberger, M Freeling 1996 The maize mutant *narrow sheath* fails to establish leaf margin identity in a meristematic domain. Development 122:1683–1691.

Semiarti E, Y Ueno, H Tsukaya, H Iwakawa, C Machida, Y Machida 2001 The *ASYMMETRIC LEAVES2* gene of *Arabidopsis thaliana* regulates formation of symmetric lamina, establishment of venation and repression of meristem-related homeobox genes in leaves. Development (in press).

Siegfried KR, Y Eshed, SF Baum, D Otsuga, GN Dress, JL Bowman 1999 Members of the *YABBY* gene family specify abaxial cell fate in *Arabidopsis*. Development 126:4117–4128.

Sinha N 1999 Leaf development in angiosperms. Annu Rev Plant Physiol Plant Mol Biol 50:419–446.

Smith LG 1996 What is the role of cell division in leaf development? Semin Cell Dev Biol 7:839–848.

Smith LG, S Hake 1992 The initiation and determination of leaves. Plant Cell 4:1017–1027.

Smith LG, S Hake, AW Sylvester 1996 The *tangled-1* mutation alters cell division orientations throughout maize leaf development without altering leaf shape. Development 122:481–489.

Steingraeber DA, JB Fisher 1986 Indeterminate growth of leaves in *Guarea* (Meliaceae): a twig analogue. Am J Bot 73:852–862.

Sylvester AW, L Smith, M Freeling 1996 Acquisition of identity in the developing leaf. Annu Rev Cell Dev Biol 12:257–304.

Timmermans MCP, NP Schultes, JP Jankovsky, T Nelson 1998 *Leafbladeless1* is required for dorsoventrality of lateral organs in maize. Development 125:2813–2823.

Traas JA, C Bellini, P Macry, P Kronenberger, D Bouchez, M Caboche 1995 Normal differentiation patterns in plants lacking microtubular preprophase bands. Nature 375:676–677.

Tsiantis M, JA Langdale 1998 The formation of leaves. Curr Opin Plant Biol 1:43–48.

Tsuge T, H Tsukaya, H Uchimiya 1996 Two independent and polarized processes of cell elongation regulate leaf blade expansion in *Arabidopsis thaliana* (L.) Heynh. Development 122:1589–1600.

Tsukaya H 1995 Developmental genetics of leaf morphogenesis in dicotyledonous plants. J Plant Res 108:407–416.

——— 1997 Determination of the unequal fate of cotyledons of a one-leaf plant *Monophyllaea*. Development 124:1275–1280.

——— 1998 Genetic evidence for polarities that regulate leaf morphogenesis. J Plant Res 111:113–119.

Van Lijsebettens M, J Clarke 1998 Leaf development in *Arabidopsis*. Plant Physiol Biochem 36:47–60.

Van Volkenburgh E 1999 Leaf expansion: an integrating plant behavior. Plant Cell Environ 22:1463–1473.

Waites R, A Hudson 1995 *Phantastica*: a gene required for dorsoventrality of leaves in *Antirrhinum majus*. Development 121:2143–2154.

Waites R, HRN Selvadurai, IR Oliver, A Hudson 1998 The *PHANTASTICA* gene encodes for a *myb* transcription factor involved in growth and dorsoventrality of lateral organs in *Antirrhinum*. Cell 93:779–789.