CROPS

Using wild relatives to improve maize

Altering maize leaf angle increases yield under high-density planting

By **Sarah Hake** *and* **Annis Richardson**

Human-mediated selection allows for the rapid evolution of crops with desired characteristics during domestication. These traits make the crops easier for humans to grow, gather, and eat (*1*). The iterative selection process during domestication restricts the diversity available in modern crop varieties for future generations of selection. Wild relatives of modern crops can therefore be a rich resource to mine for useful variants lost during domestication. Maize (*Zea mays* spp. *mays*) is one of the world's staple food and energy crops. The ancestor of maize, teosinte (*Zea mays* spp. *parviglumis*) (*2*, *3*), grows in the wild in Mexico and can be crossed with maize. On page 658 of this issue, Tian *et al.* (*4*) elegantly use the genetic diversity in teosinte to discover a useful genetic sequence that can directly increase maize yields in field conditions. This suggests that redomestication of crops may identify other useful traits hidden in crop ancestors.

Maize yields have increased throughout the past half century, in part because plants have been grown at increasing densities (*5*). This increase in yield also comes from changes in plant architecture. Increasing the density of maize has required more upright leaves to enhance their overall photosynthetic capacity and hence their ability to grow optimally (*6*, *7*). The angle of a leaf is determined by a boundary region that separates the blade from the sheath (see the figure). The blade leans away from the plant to intercept light, and the sheath wraps around the shoot to protect younger leaves and provide stiffness to the stem. The boundary region contains a ligule, an epidermal fringe that wraps tightly against the inner leaves, and the auricles on either side of the midrib, which allow the blade to lean away from the stem.

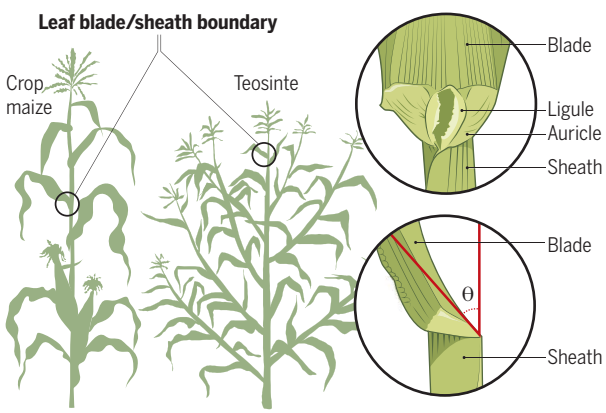
To continue to boost yield through maximizing field planting density, the maize leaf angle needs to be reduced further. Previous work in maize genetics has identified several genes that influence leaf angle. Mutations in these genes can affect leaf angle in three ways. Removing the ligule and auricles, such as in the *liguleless1* (*lg1*), *lg2*, and *liguleless narrow* mutants, results in a very upright leaf angle (*8*). Similarly, modulation of the size of the auricle, as observed when brassinosteroid (BR) hormone signaling is altered, can affect leaf angle. The application of BR to seedlings leads to larger auricles and a wide leaf angle, whereas loss of BR (or of BR signaling) leads to small leaf angles (*9*, *10*). The thickness of the leaf at the midvein (the midrib) can also affect leaf angle. For example, *drooping leaf* (*drl*) mutants lack a midrib, resulting in floppy leaves with wide leaf angles (*11*). However, in all cases, these mutants have additional effects that have a negative impact on floral patterning or overall plant stature. Therefore, despite the positive effects on leaf angle, the additional pleiotropic effects of these mutants mean that incorporating any of them into a breeding program would not be beneficial for overall crop yield. To further modulate leaf angle in crops, alternative sources of leaf angle regulation are required.

Greater genetic variation exists in teosinte because of the genetic bottlenecks that arise from domestication as certain alleles are selected and many are discarded (*12*). Tian *et al.* created recombinant inbred lines between maize and teosinte. They measured leaf angle in these lines and found two loci, *Upright Plant Architecture1* (*UPA1*) and *UPA2*, that quantitatively affect leaf angle. They identified *UPA2* as an upstream regulatory sequence. Two nucleotides are present at this location in the teosinte parent that are missing in the maize parent. Indeed, they found that no maize lines carry these two nucleotides and that only a few teosinte lines do. A more upright leaf angle is achieved when the teosinte version of *UPA2* is added to the maize version. In contrast to the *liguleless* or BR biosynthetic mutants, maize plants carrying the teosinte *UPA2* allele have normal plant height and floral branch number with only a quantitative reduction in auricle size.

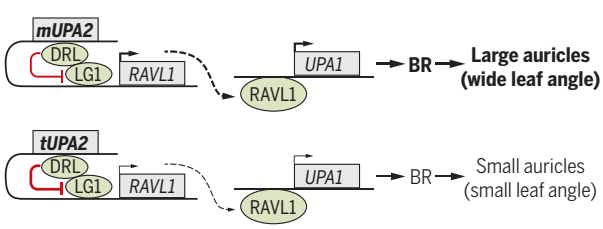
Evolutionary change often acts at cis-regulatory sequences, thereby modulating gene expression levels or affecting the timing or location of gene action (*13*). The two-nucleotide difference is within a distant cis-regulatory element nine kilobases upstream of a gene that encodes the maize ortholog of RAV-LIKE 1 (RAVL1) (*14*). RAVL1 is

Regulation of maize leaf angle

Tian *et al.* found a leaf regulatory network by comparing maize crop and parental teosinte genomes. The cis-regulatory element *UPA2* is bound by DRL, which directly inhibits LG1. LG1 binds to the promoter of *RAVL1* and induces its expression. RAVL1 binds to the promoter of *UPA1*, which encodes an enzyme that regulates the last step in BR synthesis. BR promotes auricle expansion, which regulates leaf angle.



The maize *UPA2* (*mUPA2*) sequence is weakly bound by DRL; adding teosinte *UPA2* (*tUPA2*) in maize increases DRL binding, resulting in less *RAVL1* expression and more upright leaves.



BR, brassinosteroid; DRL, DROOPING LEAF; LG1, LIGULELESS1; *RAVL1*, *RAV-LIKE 1*; *UPA2*, *Upright Plant Architecture2*.

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expressed at lower levels in teosinte than in maize. Tian *et al.* reasoned that differential regulation operating at this cis-regulatory element caused the difference in expression, and perhaps the difference in leaf angle. Indeed, when RAVL1 expression was knocked down, maize leaves were more upright. The region containing this key cis element carries a C2C2 transcription factor binding motif, which is also bound by DRL. The promoter also carries a LG1 binding site. Tian *et al.* found that DRL interacts with LG1 and dampens its positive effect on RAVL1 expression, thereby fine-tuning leaf angle. Downstream of *RAVL1* is *UPA1*, which encodes the final enzyme in BR biosynthesis (*15*). Maize lines that carry teosinte *UPA1* have larger leaf angles. Thus, by identifying two loci from teosinte, the authors were able to elucidate part of the leaf angle regulatory network, ultimately linking elements long proposed to be involved in leaf angle but with no previously known direct connections to each other.

Tian *et al.* found that the maize line in which *RAVL1* is mutated and the near-isogenic maize line carrying the teosinte *UPA2* allele have higher yields than control maize lines under high-density field conditions. They also transferred the sequences into elite crop lines, showing an increase in yield at the highest planting densities. This work highlights the power of small cis-regulatory variations, lost during domestication, to make large differences in crop yields under modern planting conditions. Overall, the hidden genetic variation in wild ancestors is revealed by generating recombinant lines and recaptured through near-isogenic lines. ■

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NEUROSCIENCE

Glia in the skin activate pain responses

A newly discovered cell type forms a network that senses painful stimuli

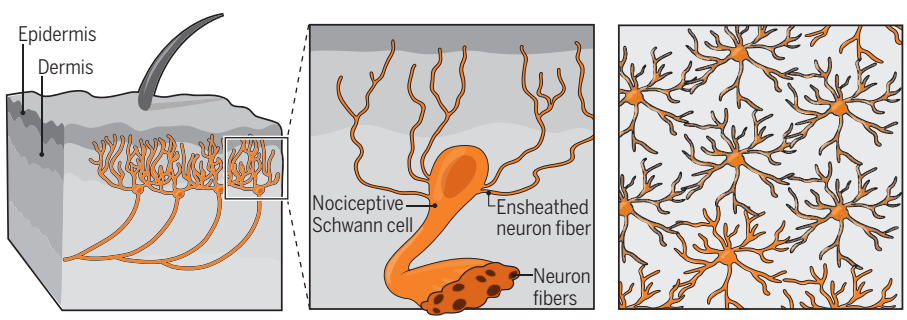
By **Ryan A. Doan** *and* **Kelly R. Monk**

The ability to rapidly perceive and react to damaging stimuli is essential for survival. In the vertebrate nervous system, specialized neural crest–derived sensory neurons in the skin, called nociceptors, detect and send signals to the brain after potentially harmful encounters. The cell bodies and axons of these nociceptors are associated with glia, non-neuronal cells that perform myriad functions in the nervous system. However, it has been a long-standing belief that nociceptors lose glial ensheathment when they cross the basement membrane into the epidermis, leaving only the free endings of unmyelinated axons as nociceptive sensors (*1*). On page 695 of this issue, Abdo *et al.* (*2*) provide evidence of a previously unrecognized specialized glial cell type, called nociceptive Schwann cells, that in direct association with nociceptive fibers project into the epidermis, where they initiate the sensation of pain. This discovery may offer new insights into future treatments for chronic pain.

Cutaneous sensory neurons are classified into myelinated A fibers with large-diameter axons and unmyelinated C fibers with small-diameter axons. A fibers are wrapped with myelin by specialized Schwann cells to promote fast nerve impulse propagation, whereas C fibers are organized into "Remak bundles" by nonmyelinating Remak Schwann cells (*3*). C fibers are more abundant than A fibers in the skin (*4*) and can respond to many forms of noxious stimuli, including mechanical, heat, and chemical. The lack of myelination may afford greater plasticity in C fibers as compared with A fibers, which is especially important in the skin, where physical insults and injuries are common (*5*). Both A and C fibers have long been thought to terminate as free endings in the skin, and non-neuronal cells in the epidermis, such as skin cells called keratinocytes, can modulate nociception (*6*, *7*). Abdo *et al.* set out to understand the relationship between non-neuronal cutaneous Schwann cells and nociceptive nerve terminals in the epidermis and found that nociceptive fibers form an intricate, mesh-like network with nociceptive Schwann cells. Notably, this network extends from the dermis into the epidermal layers of the skin (see the figure).

Detecting painful mechanical stimuli

Abdo *et al.* discovered a specialized glial cell that is directly associated with nociceptive nerve fibers that project into the epidermis. These nociceptive Schwann cells form a meshwork in the skin that activates pain responses to mechanical stimuli.



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