Background

According to the United States Department of Agriculture (USDA), corn was the largest crop grown in the U.S. in 2019 and is predicted to be the number one cereal in the world by 2020. Globally, corn has various end uses including various foods, animal feed, and ethanol for biofuel. Corn (or maize) is a very productive crop due to almost a century of intense improvement in the U.S., with yields steadily increasing since the 1930's. This improvement is due in part to advances in farming practices, but largely to genetics and breeding. The improved architecture, or shape, of maize makes it very amenable to large-scale production and harvest. One of the most effective strategies for boosting corn yield has been increased planting density, which improves with more narrow plants with upright leaf angles **(Figure 1)**.

Figure 1. Improvements to corn production since the 1930's include increasing planting density. *A comparison between a corn field from 1920 (left) and 2018 (right).*

Under dense-planting conditions, a more erect leaf angle enhances plant light interception in the lower canopy, and overall photosynthetic capacity, hence the ability to grow optimally (**Figure 2**).

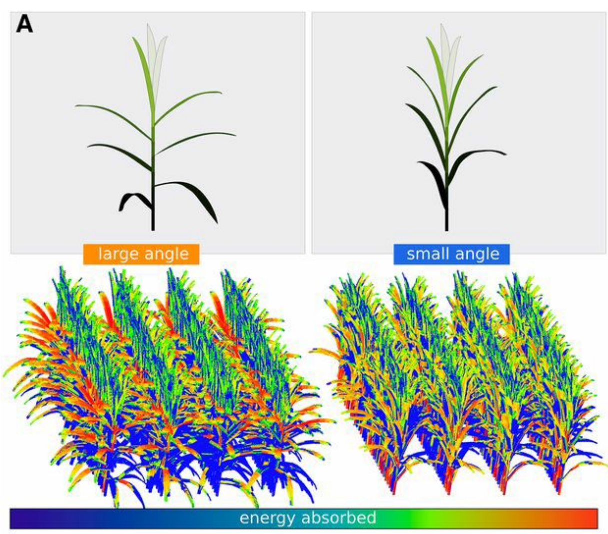

Figure 2. Leaf angle affects light distribution in crop canopies. *Schematic of corn plants and corn plots that vary in their leaf angles shows that light was distributed more uniformly and deeper into the canopies of plants with upright angles (from Truong, et al., 2015).*

Leaf angle in many cereal crops and other grasses is determined by a "boundary", which separates the leaf blade from the sheath, the part of the leaf that wraps around the stem. This boundary is referred to as the "ligule region", which includes a pair of wedge-shaped, lighter green auricles and the ligule, an epidermal fringe that wraps tightly against the inner leaves (**Figure 3**). Variation in the size and shape of auricles and ligule affect the ability of the leaf blade to bend back, and therefore leaf angle.

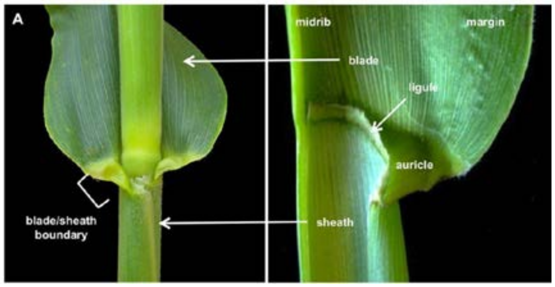

Figure 3. The structure of a maize leaf. *An intact maize leaf (left) and a leaf cut longitudinally along its midrib (right) show the distinct structures of a maize leaf including the sheath, the photosynthetic blade, and the ligule region that consists of a pair of auricles and the ligule (from Moon, et al., 2013).*

The leaf angle of a maize plant is an example of a "phenotype". Phenotype is largely controlled by an individual plant's "genotype", or genetic makeup, but can also be influenced by environmental factors. Over the years, scientists have identified genes that control development of the ligule region, and therefore leaf angle. Of interest to breeders are variations in the genetic code at these genes (or alleles), which make the plant have an optimal leaf angle for both dense planting and photosynthetic efficiency. Diversity panels of maize, which include a large variety of inbred lines with different genotypes, have been compiled and maintained by breeders and scientists. These panels retain rich genetic diversity that underlies extensive natural variation in phenotype, and provides a resource to mine for valuable alleles in breeding upright plant architecture.

Advances in high-resolution phenotyping technologies and analytics and in high-throughput sequencing are making it easier to link the diversity in phenotype to underlying sequence variants in a plant's genome. For example, it is anticipated that hand-measurements of individual leaf angles in a large field will be replaced by analyses of images captured by drone. This will rely on algorithms that not only capture phenotypic measurements of a single plant from an image (**Figure 4**), but of a whole field of plants and their influence on each other. The ability to link morphological phenotypes such as leaf angle and shape with physiological phenotypes (e.g., a plants thermal temperature in response to drought), crop improvement by breeding and/or engineering can be fast-tracked for food security in response to dynamic environments and rising world population.

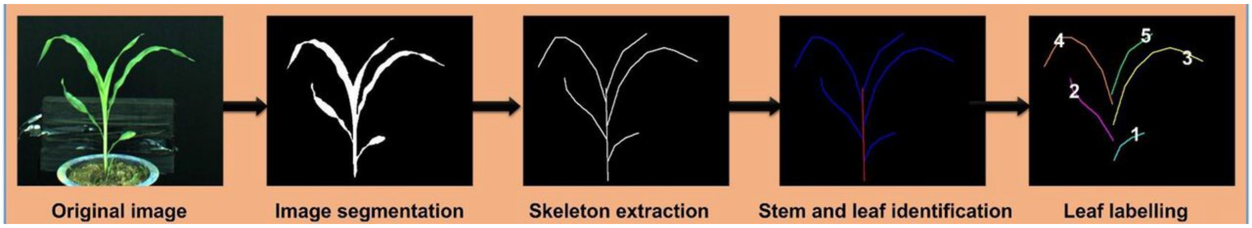

Figure 4. Computer-assisted image analysis of maize seedlings. *Image analysis software can be used to extract features from an image (such as leaves) and collect phenotypic information such as leaf number and size (from Zhang et al., 2017).*

Background references:

Truong SK, McCormick RF, Rooney WL, Mullet JE (2015) Harnessing Genetic Variation in Leaf Angle to Increase Productivity of Sorghum bicolor, Genetics, 201(3): 1229-1238

Moon J, Candela H, Hake S (2013) The Liguleless narrow mutation affects proximal-distal signaling and leaf growth, Development, 140: 405-412

Zhang X, Huang C, Wu D, Qiao F, Li W, Duan L, Wang K, Xiao Y, Chen G, Liu Q, Xiong L, Yang W, Yan J (2017) High-Throughput Phenotyping and QTL Mapping Reveals the Genetic Architecture of Maize Plant Growth, Plant Physiology, 173(3): 1554-1564