Aluminum Tolerance in Wheat—Commentary

Delhaize E, Ryan PR, Randall PJ (1993) Aluminum tolerance in wheat (*Triticum aestivum* L.) (II. Aluminum-stimulated excretion of malic acid from root apices). Plant Physiol **103:** 695–702

I propose the above article by Emmanuel Delhaize et al., which reported a game-changing breakthrough in the understanding of the mechanism of aluminum (Al) tolerance in plants. Al, the third most abundant compound in the outer crust of the Earth (lithosphere), is toxic to a majority of plants. Al toxicity is a major concern in many parts of the world, particularly in regions where acidic soils prevail, conditions that promote Al solubilization in soils. Despite the observation of mutants that show increased resistance to Al, for example, in wheat (*Triticum aestivum*), the mechanisms of Al tolerance and the underlying genes were completely unknown at the time that this article appeared. Arabidopsis (*Arabidopsis thaliana*) screening for Al-resistant mutants was difficult (though not impossible) because Arabidopsis is inherently sensitive to acidic pH, which is required for Al toxicity. This *Plant Physiology* article identified the now accepted major mechanism for Al tolerance in many plant species. The authors showed that Al tolerance is accomplished by organic acid (e.g. malate or citrate) secretion from roots. The secreted organic acids chelate Al extracellularly, inhibiting Al uptake and thus avoiding subsequent toxicity to plants. Starting with this breakthrough discovery reported in the *Plant Physiology* article, subsequent research advanced on several fronts. For example, mechanistically anion channels had been shown to provide a mechanism for malate efflux from plant guard cells and indeed Al resistance loci have been shown to encode a new class of Al-activated anion/malate channels. Many other advances were stimulated by this article, including the engineering of Al-resistant crop plants that overproduce citrate. Starting with this *Plant Physiology* breakthrough study, it is now possible to breed and engineer plants for increased Al tolerance. This article, which has been cited more than 400 times, changed the course of Al resistance research. A back-to-back article by the same lab, published in the same *Plant Physiology* issue, further described aspects of this breakthrough (Delhaize et al., 1993) and has been cited more than 180 times. An additional follow-up article by Emmanuel Delhaize and Peter R. Ryan on the breakthrough in *Plant Physiology* (Delhaize and Ryan, 1995) has been cited more than 325 times.

LITERATURE CITED

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