Crop production on acidic soils: overcoming aluminium toxicity and phosphorus deficiency

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Approximately 30% of the world’s total land area consists of acid soils, and it has been estimated that over 50% of the world’s potential arable lands are acidic (von Uexküll and Mutert, 1995). Aluminium (Al) in these soils will be solubilized into ionic forms, especially when the soil pH falls to lower than 5. These ionic forms of Al have been shown to be very toxic to plants, initially causing inhibition of root elongation by destroying the cell structure of the root apex and thus affecting water and nutrient uptake by the roots; as a consequence, plant growth and development is seriously hindered. On the other hand, phosphorous (P) is easily fixed by clay minerals that are rich in acids soils, including various iron oxides and kaolinite, and hence rendering it unavailable for root uptake. Thus, Al toxicity and P deficiency are considered to be two main constraints for crop production in acid soils.

In order to produce a better crop yield on acid soils, farmers are recommended to apply alkaline materials such as lime (primarily calcium carbonate) to increase the soil pH and thus eliminate Al toxicity, and to apply P fertilizer to increase the bioavailable P in soil. However, soil has a huge buffering capacity that is able to diminish the effects of all kinds of amendments, and the soil acidification process is accelerated by factors such as acid rain and excess application of ammonium-based inorganic nitrogen fertilizers. Hence the effects of practices such as applying lime and P fertilizer are usually not sustainable. Moreover, as application of treatments is generally restricted to the soil surface, the properties of the sub-soil are hardly modified, thus limiting the effects for crops with deep root systems. But despite all these constraints, abundant vegetation is still found on acid soils. This raises the question as to how plants deal with Al toxicity and P deficiency in acid soils? In this collection of papers relating to plant responses to Al toxicity and P deficiency, recent progress in understanding the role of the apoplast and MATE genes in Al resistance, and root morphology in plant P acquisition are reviewed, and two case studies of QTL analysis of soybean P-deficiency tolerance and a study of transgenic wheat generated by transforming a gene encoding a malate transporter are presented.

The most recognized symptom of Al toxicity is the inhibition of root elongation. Preventing Al from entering the root symplast by Al-induced secretion of organic acid anions in the root apex has, in the last 20 years, been demonstrated to be a very effective mechanism of Al resistance in plants. However, it is still a matter of debate as to whether the primary lesions of Al toxicity are apoplastic or symplastic. Updating since his last review paper published in 1995, Horst et al. (2010) summarize the recent progress in our understanding of the role of the apoplast in Al resistance and toxicity. There is accumulating physiological, biochemical and, most recently, also molecular evidence showing that modification of the binding properties of the root apoplast contributes to Al resistance. The authors suggest that further, in-depth characterization of the Al-induced apoplastic reaction in the most Al-sensitive zone of the root apex is urgently required, particularly in order to understand the mechanisms that protect the most Al-resistant plant species.

The best characterized Al-resistance mechanism is the transporter responsible for malate efflux, which was firstly cloned in 2004 by a Japanese research group (Sasaki et al., 2004). Three years later, two transporters belonging to the MATE family responsible for citrate efflux were near-simultaneously cloned in sorghum by a group from Cornell University (Magalhaes et al., 2007) and in barley by a group from Okayama University (Furukawa et al., 2007). In a review paper, Magalhaes (2010) examines the major characteristics of the transporters in the MATE family and tries to relate this knowledge to Al resistance in plants. However, the MATE family is highly flexible with respect to substrate specificity, which raises the possibility that Al resistance as encoded by MATE proteins may not be restricted to Al-activated citrate release in plant species. There are also indications that regulatory loci may be of pivotal importance in fully exploring the potential for improvement of Al resistance based on MATE genes.

Following the first cloning of the TaALMT1 gene in wheat (Sasaki et al., 2004), it was successfully transferred into an Al-sensitive barley cultivar, conferring Al resistance (Delhaize et al., 2004); however, it still remains unknown as to whether Al resistance can be improved in Al-sensitive wheat cultivars by expressing the TaALMT1 gene. In the paper by Pereira et al. (2010), particle bombardment is employed to transform wheat with TaALMT1, using the maize ubiquitin promoter to drive expression. The results showed that TaALMT1 expression, malate efflux and Al3+ resistance in nine T2 lines were significantly increased.
when compared to untransformed controls and null-segregant lines. Some $T_2$ lines displayed greater Al$^{3+}$ resistance than the Al-resistant reference genotype, ET8, in both hydroponic and soil experiments. This is the first report of a major food crop being stably transformed for greater Al$^{3+}$ resistance: so a transgenic strategy has been shown to be an effective option for increasing food production on acid soils.

Soybean is a legume plant with the ability to fix nitrogen, and P nutrition is an important factor in increasing yield on acid soils. Thus, development of P-efficient soybean varieties that can efficiently utilize both native and added P in acid soils would be a sustainable and economical approach to increasing production. Root biology is a new frontier of plant biology, and substantial efforts are now focusing on increasing soybean P efficiency through ‘root breeding’. Wang et al. (2010) summarize the possible mechanisms relating to P efficiency and consider genetic strategies to improve this efficiency in soybean, with examples from several case studies. They also highlight potential obstacles and discuss future perspectives in ‘root breeding’, providing new insights into the mechanisms of P efficiency and breeding strategies for this trait in soybean. A research paper by Liang et al. (2010) from the same group tries to identify the QTLs that confer superior root systems. By composite-interval mapping and multiple-QTL mapping, they have constructed the first soybean genetic map based on field data and from parental genotypes contrasting both in P efficiency and root architecture, and have identified 31 putative QTLs on five linkage groups that include root traits, P content, biomass and yield traits. They found that most root traits in soybean are conditioned by more than two minor QTLs, and that the region close to Satt519 on the B1 linkage group might have great potential to be utilized for future genetic improvement of soybean P efficiency through root selection.

The papers presented in this Highlight section show the rapid progress that has been made in the genetic and physiological understanding of responses of plants to acid soils and their related Al toxicity and phosphorous deficiency. There is little doubt that these findings will in the future be translated into an improved tolerance of the world’s major crops to acid soils.

**LITERATURE CITED**


