The Effect of Aluminum in Acidic Soils on Plant Growth

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Acid Mineral Soils Soil acidity, or low pH, limits plant growth in many parts of the world. Although low pH can harm plants in many ways, this article will deal only with one of these factors, aluminum (Al) toxicity.

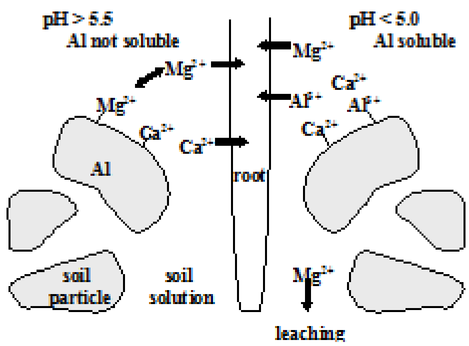
Al is the third most abundant element on the earth (after oxygen and silicon), and the most abundant metal, making up 8.1 % of the earth's crust. It is especially prevalent in clay. It becomes toxic to plants only under certain conditions.

Types and Distribution of Acid/Aluminum Soils Acidic soils are widely distributed in the tropics. Over 50%, or 2.6 billion hectares, are considered acidic (pH < 5.5). Almost a third of all tropical soils, 1.5 billion hectares, have soil acidity that is strong enough for Al to become toxic to most crop species. Most of these soils are found in the humid tropics and acid savannas, although some exist in tropical steeplands. Soils in the semiarid tropics and tropical wetlands do not tend to have this problem. Al toxicity is usually found in soils called Oxisols, Ultisols, and Dystropepts, which tend to be highly weathered soils that are low in organic matter and have low nutrient reserves.

Aluminum and Soil Chemistry Soils have five components: inorganic material, organic matter, soil air, soil water, and living organisms. Elements (including plant nutrients) can be found in various associations with these components. However, plants can take up elements only when they are dissolved in soil water. The water and these dissolved minerals are called the soil solution. As elements loosely associated with solid material are released into soil solution, they can be taken up by the plant.

When the soil pH is 5.5 or higher, Al is strongly bound to insoluble inorganic matter and so cannot be taken up by plant roots. If the pH is below 5.5, and especially below 5.0, an increasingly greater proportion of the total Al present in soils is found either in the soil solution or loosely associated with the inorganic matter (Figure 1). In this ionic form, Al^{3+} is bioavailable (can be absorbed by plant roots) and in this form may be harmful to plant growth. Although acid soils are relatively common in the tropics, Al toxicity is also thought to be one of the causes of forest decline in Europe and North America. In this case the soil pH is lowered by "acid rain" (rain that becomes acidified when certain gaseous pollutants, sulphur dioxide and nitrogen dioxide, dissolve in water droplets in the atmosphere).

Effect of Aluminum on Plants There are two major ways in which bioavailable Al (Al^{3+}) can negatively influence plant growth–it can interfere with plant uptake of the essential plant nutrients calcium (Ca) and magnesium (Mg), and it can be directly



toxic to plant roots.

Both Ca and Mg are required for plant growth, and plant roots accumulate the ionic forms of these nutrients (Ca^{2+} and Mg^{2+}) through "doors," or ion transporters in root cells. Al^{3+} can compete with these ions for uptake, causing Ca and/or Mg deficiencies in plants. These deficiencies would not occur if Al^{3+} concentrations were lower. Al^{3+} can also cause Ca and/or Mg deficiencies by increasing the amount of Ca^{2+} and Mg^{2+} leached from soils. Normally, a proportion of the Ca^{2+} and Mg^{2+} present in soils is found loosely bound to soil particles, which helps to prevent these ions from leaching away when it rains. Some of the particles to which Ca^{2+} and Mg^{2+} are bound are made up of Al. When Al dissolves at low pH, the soil has a lower capacity to hold Ca^{2+} and Mg^{2+} (i.e. the soil has a lower cation exchange capacity, or CEC), so these nutrient ions have an increased tendency to leach out of the soil. When Al^{3+} concentrations in the soil water increase as a result of low pH conditions, the Al^{3+} will compete with the Ca^{2+} and Mg^{2+} for binding sites resulting in greater leaching of these ions from the soil. The magnitude of the Al problem in soils is often expressed as the ratio of Ca^{2+} to Al^{3+} or Mg^{2+} to Al^{3+} in soil solution, because these ratios seem to do a better job of predicting the risk of Al-induced Ca or Mg deficiency than just the concentration of Al^{3+} alone. Finally, independent of the Al^{3+} concentration, the ability of a plant to accumulate essential ions such as Ca^{2+} and Mg^{2+} is lower when the soil pH is below 5 than it is at a more neutral (6-7) pH.

The bioavailable form of Al can also be toxic to plant roots. The mechanism by which this occurs is not well understood, but greater damage seems to occur to root tips. Al^{3+} reduces both root cell division and root elongation, resulting in short, stubby roots. This in turn reduces the ability of roots to supply water and necessary nutrients to the plant. Phosphorus deficiencies can be more pronounced when the growth of a plant's root system is inhibited. This is because phosphorus is not very mobile in soil and so plants benefit from an expanding root system that can "mine" phosphorus from a large volume of soil. Al^{3+} will also react with phosphorus in the soil solution, making it less available to plant roots.

So the effect of aluminum toxicity is primarily caused by nutrient deficiencies (such as a lack of Ca and Mg) or an inhibition of root elongation. Both Ca and Mg are essential macronutrients for all plants. The Ca content of plants typically ranges from 0.1% to >5.0% of dry weight. Ca requirements tend to be lower in monocots (grasses) than dicots (broadleafed species). Symptoms of Ca deficiency include death of young leaf blades and of the growing tips of plants. The Mg content ranges from 0.15 to 0.35% of the dry weight of plant tissue. Deficiency symptoms include chlorosis (yellowing) of older leaves between the veins or chlorosis appearing as blotches. If the deficiency continues, these areas of tissue will eventually die. As mentioned, Al^{3+} inhibits root elongation resulting in short, stubby root systems. Root tips may eventually turn brown.

Aluminum Content of Plant Tissues When the bioavailability of Al increases, the accumulation of Al in plant tissues also increases. Unlike other metals such as cadmium, Al does not appear to accumulate to high concentrations in plant tissue. Al concentrations in plant tissue are relatively low, with roots tending to contain more Al than stems, leaves, seed or fruit. Al concentrations ranged from 850 to 3500 ppm (mg Al per kg plant tissue) in a study done in tea plantations in China. The amount of Al in tea leaves was found to depend on soil pH, and increased as the leaves aged (Dong *et al*., 1999, Comm Soil Sci & Pl Anal 30(5&6): 873-883). When native vegetation on acidic high-aluminum soils was sampled in Brazil, the Al content of leaves ranged from 60 to 16400 ppm (Geoghegan and Sprent, 1996, Comm Soil Sci & Pl Anal 27(18-20): 2925-2934). In another study, as little as 13 ppm in maize roots was enough to result in a reduction in root length (Lindon and Barreiro, 1998, J Pl Nutr 21(3): 413-419).

The consumption of Al has been linked to certain human diseases (including possibly Alzheimer's, although this link is controversial). It is very important to realize that different forms of Al are more or less bioavailable (and therefore potentially more or less harmful) to humans. For example, ionic Al (Al^{3+}) that might be released when cooking foods in an aluminum pot is considerably more bioavailable when consumed than is Al incorporated into plant tissue. Little is known about the relative bioavailability of different forms of Al. The diets of Americans and Europeans are thought to contain less than 150 mg of Al per day. As a comparison, people taking prescription antacids in the 1970s and 1980s often consumed 1 to 3 g of Al per day (Greger and Baier, 1983, Am J Pl Nutr 38: 411-419). It is believed that inhalation or ingestion of dust and dirt is a greater source of Al for humans than is the consumption of food containing Al. We are unaware of any complaints of human health problems specific to regions where Al toxicity to plants is a serious problem.

Reducing the Effects of Aluminum on Plants Very typically, different plant species (or cultivars within a species) differ in their ability to tolerate stresses imposed on them, and this is true for Al^{3+} stress as well. Plants have mechanisms to cope with Al^{3+} when it is present and these mechanisms work more efficiently in some species or cultivars than in others. If you are growing plants in an area where you believe soils are acidic and may contain relatively high amounts of bioavailable Al^{3+}, one thing you can do is ask seed companies if they have Al^{3+} tolerant varieties. You can also conduct your own variety trials to determine if suitable crops that are known to tolerate Al^{3+} can be grown in your area.

Crops such as pineapple (*Ananas comosus*), coffee (*Coffea sp*.), tea (*Camellia sp*.), rubber (*Achras zapota*), and cassava (*Manihot sp*.), as well as pasture species such as guinea grass (*Panicum maximum*), jaragua (*Hypaahanea rufa*), and molasses grass (*Melinis minutiflora*) can grow in soils with bioavailable Al concentrations that would not support corn and soybean.

There are also large differences between cultivars within the same species. It is possible that if you are in an area with acidic soils, locally selected varieties may have been chosen partially for their ability to tolerate Al^{3+}. In a study of the variation in response of various sorghum varieties to Al^{3+}, it was found that genotype SC0283, which originated in Tanzania, was the most tolerant of all the cultivars tested. The genotypes CS3541 (India), SC0112 (Ethiopia), and SC0056 (Sudan) were somewhat tolerant, while SC0170 (Ethiopia), P721, and NB9040 (both from the US) had little or no tolerance (Duncan et al., 1983, Agron J 75(6): 10231026). Another study on amaranth found a very wide range in the ability of different species to tolerate Al^{3+}. In that study it was discovered that different strains of *Amaranth tricolor* L. (S-30, S-99, S-133, and S-69) grew best on Altoxic soils, while 6 strains of *A. cruentis* L. (S-1011, S-53, S1, S-27, S-31, and S-40) and a *A. hypochondriacus – A. dubius* L. (strain S-94 Type A) mixture fared the worst. Three strains of *A. hypochondriacus* L. (S-224 Type A, S180, and S-122) and a strain of *A. caudatus* L. (S-122) grew moderately well in the Al-toxic soil (Foy and Campbell, 1984, J Pl Nutr 7(9): 1365-1388).

Tolerant species or varieties seem to be able to do one or a combination of the following: suffer less injury to roots, raise soil pH near the root surface (so that Al^{3+} precipitates and becomes less bioavailable), secrete organic acids to form complexes with the Al^{3+} (so that Al becomes less bioavailable), translocate less Al to plant tops, and have a strong ability to accumulate Ca^{2+} and/or Mg^{2+} despite the presence of Al^{3+}.

Adding lime to the soil can reduce Al toxicity, since Al is toxic to plants only when it is soluble and Al solubility is strongly dependent on soil pH. As the pH increases from below 5.0 to between 5.5 and 6.0, Al^{3+} will precipitate out of the soil solution and will no longer be bioavailable to plant roots. It is important not to raise the pH too much, however, since many tropical plants are adapted to growing in slightly acidic soils (pH of 5.5-6.0) and will not grow well if the pH is neutral (7.0). While adding lime may improve the conditions of the surface soil, the subsoil will remain quite acidic.

Adding organic matter to soil is another good way to reduce Al bioavailability. Organic matter has the ability to bind Al^{3+}, reducing its bioavailability and its ability to harm plant roots or to compete with Ca^{2+} or Mg^{2+} for uptake.

As already mentioned, plants growing in acidic soils high in Al may also suffer from a deficiency in phosphorus (P), because P is not very mobile in soil, and because Al^{3+} reacts with P, reducing its bioavailability. Al^{3+} also inhibits root elongation and the ability of root systems to “mine” large volumes of soil for P. When plants have a healthy relationship with mycorrhizas, the accumulation of P may be improved. Mycorrhizas are fungi that associate with plant roots enabling greater accumulation of plant nutrients, especially P. It has been shown that as much as 80% of the P found in plant shoots has been removed from soil by mycorrhiza associated with plant roots. Plant-mycorrhizal associations are lower when soils are particularly saline, waterlogged, or disturbed (from tillage), or when soil has extremely high or low fertility. Associations arise from a preexisting network of fungi in the soil

Conclusion Acidic soils are quite widespread in the tropics. Although Al is present and not harmful to plants in many soil types, in acidic soils the Al can dissolve into the soil solution and become bioavailable to plants. Al^{3+} can harm plants by inducing Ca and Mg deficiency, and/or by damaging plant roots directly. The damage can be lessened by choosing crops or cultivars tolerant of Al^{3+} stress, and by using management strategies aimed at reducing the bioavailability of Al^{3+}, such as raising soil pH and increasing soil organic matter. Increasing the amounts of Ca and Mg in soil may help as well. Full references available upon request.

