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Constraints of highly weathered soils, especially soil sodicity, to plant production in the dry tropics

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Abstract

The properties of good arable soils are briefly reviewed and compared with the characteristics of the highly weathered soils that are commonly found in the dry tropics of northern Australia. Constraints to plant growth include low fertility; shallow, gravelly profiles; high salt contents; and adverse soil chemical properties such as soil acidity and soil sodicity. The role of exchangeable cations in the soil solution is explored as a control over soil sodicity that may produce a range of soil properties that are adverse to plant growth and tree production. The origins of soil sodicity are discussed and methods of amelioration of soil sodicity by use of gypsum are explored.

Keywords: soil constraints, exchangeable cations, sodic soils, slaking, dispersion, gypsum,

INTRODUCTION

The term “tropical soil” is an imprecise term and means “any soil that occurs in the tropics”. Many tropical soils conform to the stereotype of old soils that have deep profiles, extending to depths of 5 m or more, red colours, and chemical properties that are often dominated by iron compounds, strongly acidic conditions, and generally low to very low inherent fertility.

Other tropical soils, however, may have developed on young erosional or depositional surfaces and may be associated with stream terraces where the soils receive regular applications of silts and clays as a consequence of regular flooding during wet seasons. If the soil parent material is relatively fresh and unweathered, and the climate is moist and warm, the soil will support vigorous plant and animal life. Decomposition of the organic matter returns nutrients to the soil to support subsequent plant growth. But the nutrient supply is not without limits!

Weathering of minerals and soil-forming processes over a prolonged period, driven by seasonally moist, tropical conditions, will liberate and leach away even the slowly soluble nutrients from the soil. Such soils are characterised by:

- major losses of minerals and associated plant nutrients;
- the accumulation of virtually insoluble residues that have resisted leaching;
- an inability to supply and retain life-giving nutrients to plants and animals.

The soils that remain are impoverished, widespread in the tropics, and are often over-utilised, especially in Third World countries (Uehara & Gillman 1981).

PROPERTIES OF GOOD, ARABLE SOILS

Good arable soils present few limitations, if any, to land use and are capable of being cultivated to support crop production. They are characterised by a variety of soil properties including:

- a reasonable depth of soil, ideally with topsoils of 100 - 200 mm or more thick, and profiles 1 - 2 m deep. These topsoil and profile thicknesses guarantee an adequate zone for plant roots to exploit as an anchor for the plant, and as the reservoirs of essential nutrients and water on which all plant growth relies.

- low content of gravel in the soil. “Gravel” consists of particles coarser than 2 mm and occupies space in the soil profile that would otherwise be occupied by water, soil, and plant nutrients. Soils with a high gravel contents (more than 25% of the whole soil) act like shallow soil profiles in the limitations they impose on root growth, and on the sizes of the water and nutrient reservoirs that can be accessed by the plant roots.

- good soil structure characterised by well-connected coarse pores that allow water to infiltrate into the soil, and to drain from the soil profile, preventing waterlogging when large volumes of water infiltrate during heavy rainfall or irrigation events. Good soil structure is also characterised by well-developed aggregates with fine pores that store water in the soil and can be extracted and used by growing plants.

- an adequate plant nutrient supply. Plant nutrients are derived from decomposing organic matter and the weathering of minerals or fertilisers. They are taken up by plants in a soluble form through their root hairs; nutrients may also be applied as foliar fertilisers and are absorbed through the plant leaves. A good arable soil will contain adequate supplies of organic matter that give the soil a dark colour, an organic carbon content of at least 2%, a bicarbonate-extractable (Colwell) phosphorus content of at least 20 mg/kg, and a cation exchange capacity of more than 4 meq/100g of soil, which is equivalent to 4 cmol/kg of soil.

- beneficial (non-toxic) soil chemical properties, meaning that the soil will be non-saline (electrical conductivity less than 0.25 dS/m; chloride content less than 300 mg/kg), not too acidic nor too alkaline (pH of 6.0 - 7.0), and will be non-sodic (exchangeable sodium as a percentage of the cation exchange capacity of less than 6%).

DEALING WITH SOIL CONSTRAINTS TO PLANT GROWTH

Low soil fertility

Soil fertility problems should be identified by chemical analysis by a reliable laboratory of representative samples of both the topsoil (0 - 10 or 20 cm depth) and the subsoil (50 - 60 cm). The constraint can be overcome by adding fertiliser or manure, targeted by both composition and amount, to the needs of the plants as identified by a reputable forester, agronomist, or horticulturalist.

Shallow or gravelly soil profiles

The major problem to overcome is the small water and nutrient reservoirs that shallow and/or gravelly soils offer to growing plants. Except where there is a very hard rocky substrate, the soil depth can be increased by deep ripping to whatever depth can be achieved with the machinery available, and preferably to a minimum of 60 cm. The small water reservoirs will have greatest impact on the establishment of seedlings and can be supplemented by irrigation until the plants become established and develop an adequate root system.

High salt contents in the soil

Satisfactory plant growth in saline soils depends on a number of factors including the physiological constitution of the plant, the stage of growth of the plant, and the plant's rooting habits. Soil factors to be considered include the structure of the soil, soil drainage and aeration, the composition of the salts present, the proportionate amounts of the salts, the total concentration of the salts, and the salt distribution through the soil profile.

The only practical way to deal with strongly saline soils is to leach out the salts. Effective leaching requires access to a plentiful supply of high quality water, effective soil drainage capability, saline water retention and management systems, and a salt disposal system.

As a rule of thumb, 100 mm of water will generally remove 70 – 80% of the soluble salt from a 10 cm thick layer of soil.

Frequently, saline soils are fine textured, have a high water table, or, in drier areas, may have a dense gypsum layer in the subsoil. These conditions will reduce the movement of rain-fed or irrigation water down the soil profile and make it difficult to leach the salts to the desired depth below the plant rootzone. Similarly, in salty soils that have a high watertable (often in coastal lowlands), artificial drainage is necessary before the excess salts can be removed. In soils with impervious layers, deep ripping, deep chisel ploughing, or expensive drainage systems may be needed to open the soil up to the beneficial, leaching effects of percolating waters.

Adverse soil chemical properties (acidity, sodicity)

Most of the commonly occurring detrimental chemical properties of soils can be altered by using soil ameliorants of various kinds.

Soil acidity can be reduced (i.e. the soil pH can be raised) by the use of lime, dolomite, or Minplus rock dust (Coventry *et al.* 2001). The latter can also be used to reduce the capacity of highly weathered soils to lock up, or "fix" phosphorus that is applied to the soil in the form of phosphatic fertilisers.

Soil alkalinity can be reduced (i.e. soil pH can be lowered) by the application of sulphur, nitrogenous fertilisers especially ammonium sulphate, or by growing legumes that have a slow acidifying effect on the soil.

Soil sodicity is a widespread but poorly understood problem of the soils of the dry tropics (Naidu *et al.* 1992). The nature of soil sodicity, the adverse properties of sodic soils on plant growth, and manner in which gypsum can ameliorate those adverse properties is the focus for the rest of this paper.

EXCHANGEABLE CATIONS IN THE SOIL

In order to understand the nature of cations in the soil, it is useful to explore the nature of crystalline materials and what happens when they dissolve in water. Crystals of common salt $(NaCl)$ are three dimensional lattices of equal numbers of sodium cations (Na^+) and chloride anions (Cl^-), which are assembled in regular arrangements by ionic bonds. Electrical neutrality is maintained in the crystals by the balance between the positive and negative charges that hold the crystal together.

When common salt dissolves in water (H_2O), sodium cations and chloride anions are released into the water in large numbers. The ions are surrounded by water molecules (i.e. they become "hydrated"). Again, equal numbers of ions of opposite charges ensure electrical neutrality in the solution.

The plant nutrient supply consists of hydrated cations (+) or anions (–) in the water in the soil (i.e. in the "soil solution"). Ions are released from organic matter by microbial decomposition, from mineral grains or fertilisers by weathering, and from the dissociation of water molecules, as follows:

$$H_2O \rightarrow H^+ + OH^-$$

The nutrient ions are held in a dissolved form in the soil solution, on the surfaces of fine mineral particles, and on the surfaces of very fine particles of organic matter (humus). In the soil, the inorganic minerals and the humus particles generally carry a net negative charge and attract nutrient cations from the soil solution. Electrical neutrality is preserved, again, by cations being held loosely on the surface of the colloid, forming a diffuse double layer, and neutralising the negative charges on the colloid.

Cations at the particle surface often swap places ("exchange") with other cations in the soil solution. The cation exchange processes involve 4 basic and 2 acidic cations that carry different amounts of positive charge:

Exchangeable basic cations: Ca^{2+}, Mg^{2+}, K^+, Na^+ (calcium, magnesium, potassium, and sodium, respectively)

Exchangeable acidic cations: H^+, Al^{3+} (hydrogen and aluminium)

The cation exchange capacity (CEC) of a soil is defined as the capacity of a soil to hold cations on colloid surfaces, and to supply those nutrient cations to soil solution for uptake by growing plants. Hence, the CEC of the soil is a good measure of soil fertility. The CEC of the soil is dependent on the amount of negative charge on the colloid surface and on the amount of colloid surface present in the soil (i.e. on the fineness of the colloidal mineral and humus particles present).

Much of the behaviour of colloids in the soil is controlled by the relative proportions of exchangeable sodium (Na^+) and calcium (Ca^{2+}) cations in the soil and soil solution.

Sodium-dominant soils: are very reactive when placed in water. The soil aggregates will slake, disperse, and break down. The fine particles released by these processes fill up and choke the soil pores, form crusts, and inhibit water infiltration into the soil.

Calcium-dominant soils: are stable when placed in water. They form aggregates, make pathways for water movement through the soil, and enhance water infiltration and storage in the soil.

SODIC SOILS

Sodic soils are soils with a relatively high content of exchangeable sodium in the cation exchange complex of the soil. The extent to which this constraint influences soil behaviour is measured by the *Exchangeable Sodium Percentage (ESP),* which is determined from a chemical analysis of the exchangeable basic and acidic cation contents of the soil, as follows:

ESP = 100 x Exchangeable sodium / (sum of exchangeable basic + acidic cations)

ESP = 100 x Exch Na / (Exch Ca + Mg + K + Na + H + Al)

In these formulae, the cation contents are in meq / 100 g of soil, equivalent to $cmol_c$ / kg soil, and it is recognised that the exchangeable acidic cation contents are often not determined by soil analysis, and may be omitted from the calculations.

The exchangeable sodium percentage allows the definition of soil sodicity classes, as follows:

Non-sodic: ESP less than 6 %
Sodic: ESP between 6 and 15 %
Strongly sodic: ESP greater than 15 %

Sodic and strongly sodic soils present a range of adverse properties, including:

- poor surface soil structure,
- surface crusts, poor tilth, enhanced runoff and erosion,
- poor seedling emergence and extremely poor early plant growth,
- little soil protection from rain, wind, and overland flow,
- slow water infiltration into topsoils and subsoils,
- groundwater perching on top of subsoil horizons,
- accelerated sheet, rill, gully, and wind erosion,
- tunnel and piping erosion,
- poor soil stability and poor load-bearing characteristics.

The combined effect of all of these conditions is poor plant establishment and poor plant growth (So and Aylmore 1993; So *et al.* 1995). They all impact dramatically and detrimentally on the productivity of sodic soils that are widespread in the dry tropics of northern Australia (Fig. 1).

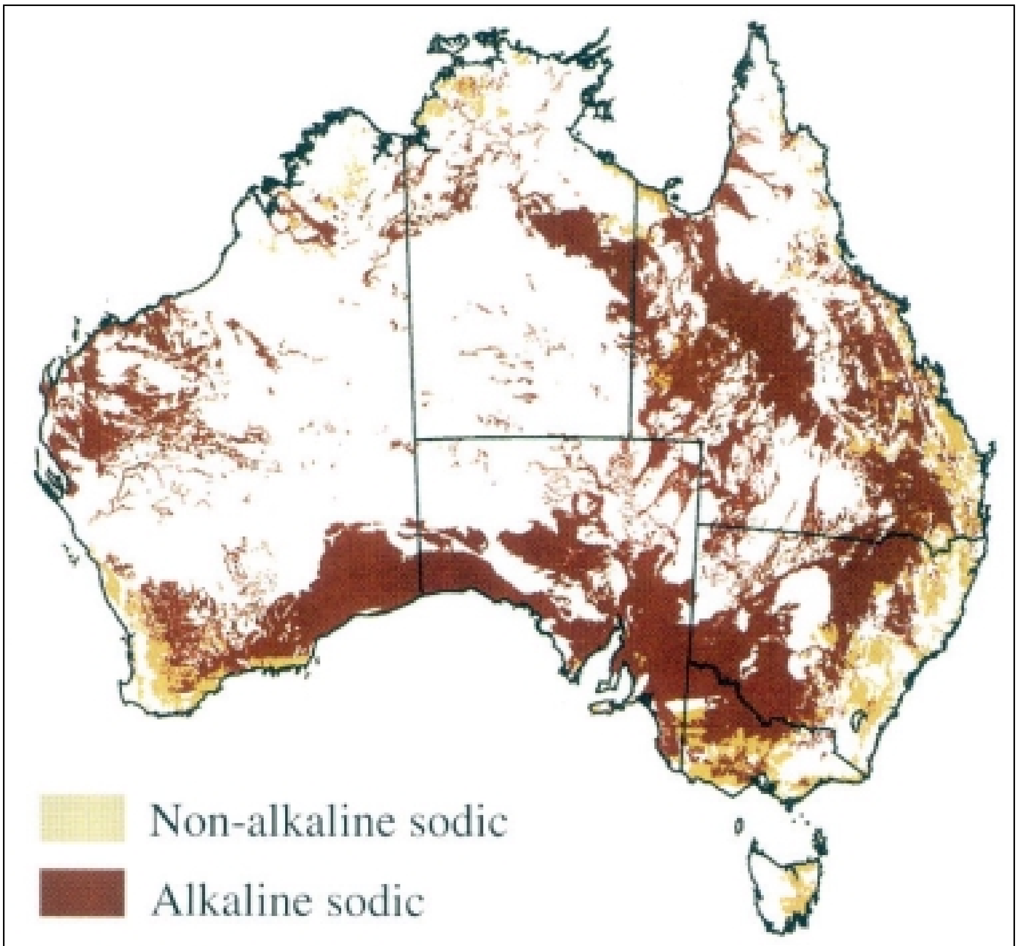

Figure 1. The distribution of sodic soils in Australia. Source: Hamblin (2000).

AMELIORATION OF SODIC SOILS

The differential attraction of exchangeable cations in the diffuse double layer that forms at a soil colloid surface, as follows, offers a mechanism for making a permanent change to the chemical properties of sodic soils:

$$H^+ > Al^{3+} > Ba^{2+} > Ca^{2+} > Mg^{2+} > K^+ = NH^{4+} > Na^+$$

(tightly held) *(weakly held)*

In this sequence, it is evident that calcium cations are more strongly held to the surfaces of soil colloids than are sodium ions. Hence, if the soil solution were saturated with calcium ions, they would push the more weakly held sodium cations off the colloid surface, and an important change in the behaviour of the sodic soil would be effected.

Hence, many of the poor physical characteristics of dispersed sodic soils can be ameliorated by the addition of calcium ions from:

gypsum	$CaSO_4$
lime	$CaCO_3$
dolomite	$CaMg(CO_3)_2$

Of these soil ameliorants, gypsum is the most readily soluble source of calcium ions, and the most cost-effective: 1 tonne of gypsum currently costs approx. $120 to buy and spread in the Townsville area.

Gypsum applications provide a source of calcium ions. The calcium ions displace sodium ions from the surfaces of colloids of sodic soils. If sufficient gypsum has been applied, the calcium-dominated colloids will form aggregates and open up leaching pathways in the soil, thereby allowing the further amelioration of the sodic soil by the gypsum-derived calcium ions in percolating water.

Loveday and Bridge (1983) have shown some dramatic examples of the effect of gypsum on the total porosity of sodic soils and on the enhanced interconnections between pores. The greater permeability of the gypsum-treated soil allows much freer entry of irrigation or rainwater, which then becomes a much more effective leaching agent to remove soluble salts from soils that are both saline and sodic.

Which soils will respond to gypsum?

A simple field test, following Emerson (1983) can be carried out to determine if a soil will respond to gypsum applications. Drop a small soil aggregate (5 - 10 mm) into a cup of rainwater or deionised water *(avoid salt-enriched bore water).* Take another soil sample, manipulate the soil with a small amount of water to produce a plasticine-like bolus, form the bolus into a cube of about 10 mm, and then drop the cube into another cup of water. Do not bump or move the cups. Observe the samples after a few minutes, after 1 hour, and after 16 hours (overnight).

You will observe:

No change: the soil is not responsive to gypsum.

Small particles flake off the clod of soil or the soil bolus (slaking): gypsum will be of marginal benefit; build up the soil organic matter content.

A halo of fine, smoke-like particles is liberated (dispersion), the halo may spread as a cloudiness through the water. The greater the turbidity of the water, the more responsive to gypsum the soil will be.

HOW MUCH GYPSUM IS REQUIRED TO AMELIORATE A SODIC SOIL?

As a rule of thumb, gypsum should be applied at rates of 5 - 25 + tonnes / ha, which is equivalent to 0.5 - 2.5 + kg / m^2. There are soils in the Townsville area that require up to 70 t/ha of gypsum to overcome their extremely sodic properties!

The gypsum requirement of a sodic soil can be determined by use of GYPSY, a computer program developed by the Cooperative Research Centre for the Sustainable Production of Sugar. The calculations depend on the cation exchange capacity, CEC; the exchangeable sodium percentage, ESP; the electrical conductivity, EC; and the chloride content of the topsoil (0-15 cm depth) and the subsoil (50 – 60 cm depth).

Calculating the gypsum requirement of a sodic soil

The amount of gypsum required to ameliorate a sodic soil can be calculated as shown in the following example taken from Brady and Weil (1999, p. 398).

Given a sodic soil that has an ESP of 25% and a CEC of 18 cmol/kg, how much gypsum is required to reduce the ESP of the uppermost 30 cm of the soil to 5% to overcome the soil's sodicity and allow it to grow a crop?

1. The following reaction will occur:

$$\boxed{\textbf{Sodium-dominated clay}} + \underset{\text{(gypsum)}}{CaSO_4 . 2H_2O} \rightarrow \boxed{\textbf{Calcium-dominated clay}} + Na_2SO_4 + 2H_2O$$

2. Determine the amount of Na^+ ions to be replaced:
   Multiply the CEC of the soil (18 $cmol_c$/kg) by the change in Na^+ saturation desired (25 – 5 = 20%):
   18 cmol/kg x 0.20 = 3.6 cmol/kg

3. The Na^+ will be replaced by an equivalent weight of Ca^{2+} in the gypsum.
   Hence, 3.6 $cmol_c$/kg of $CaSO_4 . 2H_2O$ will be required to replace 3.6 $cmol_c$/kg of Na^+.

4. Calculate the weight in grams of gypsum to provide 3.6 $cmol_c$/kg of soil:

   4a. Determine how many g of $CaSO_4 . 2H_2O$ there are in 1 $cmol_c$

   To do this, divide the molecular weight of $CaSO_4 . 2H_2O$ (172) by 2 (because Ca^{2+} has two charges and Na^+ has one), then by 100 to reduce $moles_c$ to $centimoles_c$

   172 / 2 = 86 g $CaSO_4 . 2H_2O$ / mol_c
   86 / 100 = 0.86 g $CaSO_4 . 2H_2O$ / $cmol_c$ required to replace 1 $cmol_c$ of Na^+

4b. For each kg of soil, 3.6 cmol_c of Na^+ would require:
3.6 cmol_c/kg x 0.86 g/cmol_c = 3.1 g $CaSO_4 . 2H_2O$ / kg of soil.

5. Now, calculate the volume of soil (kg) in 1 ha (100 m x 100 m) to the depth to be ameliorated
[30 cm = 0.3 m]:
Volume = 100 x 100 x 0.3 m^3 = 3,000 m^3

6. Calculate the mass of soil in 3,000 m^3, assuming a bulk density of 1.3 Mg / m^3 (equivalent to 1.3 g / cm^3):
Mass = volume x bulk density = 3000 x 1.3 = 3,900 Mg = 3.9 million kg

7. Amount of gypsum required = 3.1 x 3.9 x 10^6 g = 12.09 x 10^6 g **= 12.1 tonnes / ha**

NOTE: Impurities in the gypsum, and inaccuracies in the system, may lead to an upward adjustment of 20 – 30% in the amount of gypsum required.

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