

Diagnosis and Management of **Sodic Soils** under **Sugarcane**



TECHNICAL PUBLICATION

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Diagnosis and Management of Sodic Soils under Sugarcane

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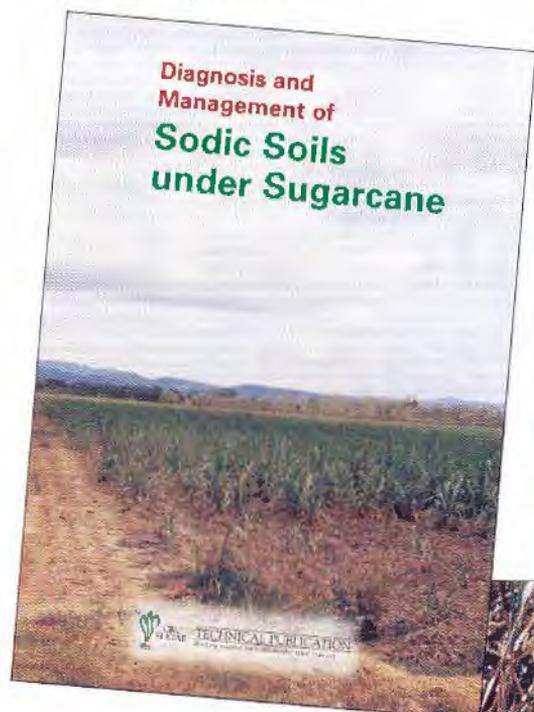


What is this manual about?

Soil sodicity has a marked detrimental effect on sugarcane growth and yield. This manual deals with the diagnosis and management of sodicity and related problems in the soils and irrigation waters of the Australian sugar industry.

This manual is part of a toolkit designed for use by extension officers, agribusiness consultants and growers in the Australian sugar industry. The other components of the toolkit are a diagnostic Field Kit and a computer program *Gypsy*, used for gypsum rate calculations.

Throughout the manual, words and abbreviations that may be unfamiliar are defined in the *Glossary* section.



Sodic Soils Manual

Sodic Soils Field Kit



Gypsy

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Why are sodic and saline soils an issue?

EFFECTS OF SODICITY AND SALINITY ON SUGARCANE GROWTH

Typical effects of sodicity on crop production include reduced plant populations and poorer growth of these populations. Growth restrictions are due to waterlogging, poor infiltration and availability of water and limited rooting depth. Spalding (1983) investigated the relationship between yield, commercial cane sugar (CCS), and soil sodicity and salinity in a rain-fed block in the Mackay district. Growth was variable across the block and 15 plots were chosen to cover the range of yields. Yield was best correlated with the exchangeable sodium percentage (ESP) of the 0.25–0.5 m depth layer. The relationship was linear, decreasing from a yield of 100 t/ha at ESP 0 to 0 t/ha at ESP 66 (a decrease of 1.5 t/ha for each 1% ESP).

Nelson and Ham (2000) carried out a similar study at 16 irrigated sites in the Burdekin district. The combined effects of soil sodicity and salinity accounted for 79.5% of the variation in yield across all sites. Although there were differences between sites, there was no consistent effect of variety or crop class. Over all sites, yield decreased by 2.1 t/ha for each 1% increase in ESP in the 0.25–0.5 m depth layer (Figure 1). The more pronounced effect of sodicity in the Burdekin was attributed to higher potential yield at low levels of sodicity in the Burdekin.

Sodicity and ameliorative treatments have small and variable effects on CCS. In general, the effects on yield far outweigh any effects on CCS. Different varieties may vary in their tolerance of sodicity and ratoon crops usually suffer more than plant cane, but in general, yield is reduced by sodicity.

Sodic layers deeper than 0.6 m are generally not considered to restrict growth, but they may reduce drainage through the profile (Ham *et al.*, 1995).

It has been conservatively estimated that soil sodicity reduces the annual industry cane production by 500,000 tonnes (Ham *et al.*, 1995).

Crop symptoms of sodicity are not unique, so soils must be analysed in order to diagnose the problem. Irrigation water also plays an important role, and it too should be analysed.

How does sodicity affect growth?

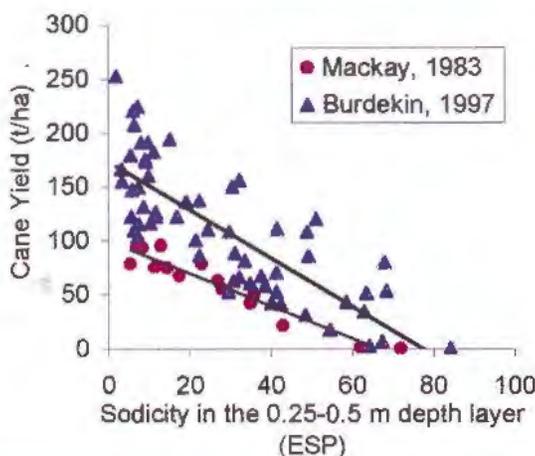
Sodic soils have low structural stability when wet, which results in undesirable properties for crop growth. Cultivation at the correct water content may produce a friable structure in the cultivated zone. However, as soon as the soil wets up, the soil structure becomes unstable; large pores collapse and small pores become clogged.

Permeability to water rapidly reduces as pores collapse, so the wetting front is arrested before moving very deep. Irrigation water may only move 100 mm or so into the soil. Permeability to air also decreases, causing the soil to become anaerobic. The ability of wet sodic soil to withstand mechanical stresses is very low, resulting in soupy and boggy behaviour.

Because permeability is so low on sodic soils, water either runs off, or if the soil surface is flat, the water stands for long periods of time, causing waterlogging symptoms in the crop (Figure 4).

As the soil dries, the particles pack together, forming a dense and hard mass with few pores, cracks or aggregates. It becomes very difficult for roots to penetrate. The moisture range at which effective cultivation is possible is very narrow;

FIGURE 1: Sugarcane yield is directly related to soil sodicity. The graph shows data from 16 sites in the Burdekin (Nelson and Ham, 2000) and one site at Mackay (Spalding, 1983).



when dry the soil breaks up into large hard clods or pulverises to bulldust. Even when the soil is moist, the availability of the water to plants is low, due to a lack of root proliferation and because there are few pores of the size that hold water in the plant available range (Figure 2).

Most of the water is held in pores too small for roots to be able to extract it. The result is long periods of water stress for the crop (Figure 6).

Under rainfall or irrigation, runoff is high and infiltration is low, even under low application rates (Figure 3). In furrow irrigated rows, water does not soak up into the hill. Sugarcane may show symptoms of water stress as soon as a few days after irrigation or rainfall.

Also, crops in these blocks are slow to ratoon. The cane typically shows poor growth and lack of stool except at the bottom end of cane fields where water lies in the rows. The problem may not appear while the cane is still being cultivated as cultivation roughens the soil and opens cracks and air-spaces that slow the flow of water and enable adequate water penetration.

The soil behaviour described above may not necessarily be obvious at the surface, as sodic soils frequently are not very sodic in surface layers. However, the soil behaves similarly at depth, restricting water entry and root penetration.

Poor water penetration and low plant available water contents may also be due to factors other than sodicity, such as salt concentrations in the soil and water being excessively low or high.

OTHER EFFECTS OF SODICITY

Nutrition and disease

Although the main effects of sodicity on plant growth are due to poor structural stability, there are some nutrition problems that are related to sodicity. As sodic soils are low in organic matter, have low microbial activity and are frequently waterlogged, they have a low capacity to supply nitrogen. However, normal application rates supply more than enough nitrogen, because of the low yield potential on sodic soils.

Zinc deficiency has been associated with sodic and alkaline soils in other crops, but does not appear to be an issue for sugarcane. Iron deficiency can occur in soils with high pH, but it is normally temporary

FIGURE 2: In sodic soils, the volume of large and medium size pores is less than in nonsodic soils. As a result, sodic soils are often too wet or too dry for effective cultivation and root growth and functioning.

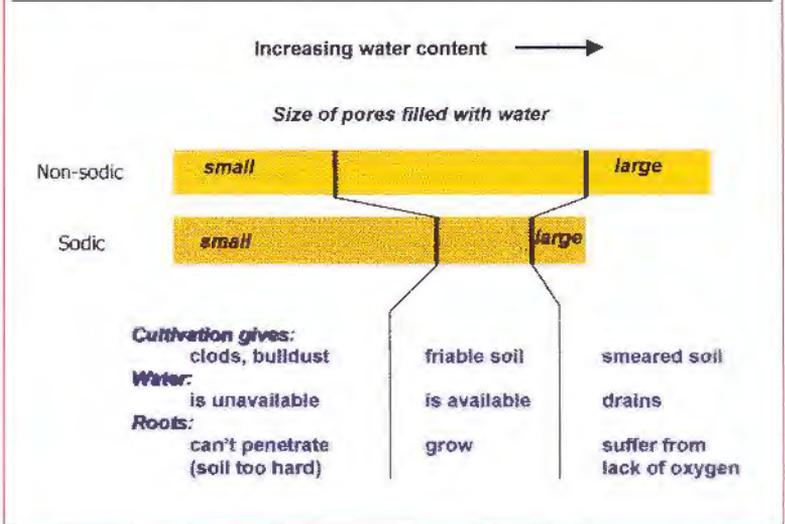


FIGURE 3: Sodicity and infiltration rate (from Kazman *et al*, 1983).

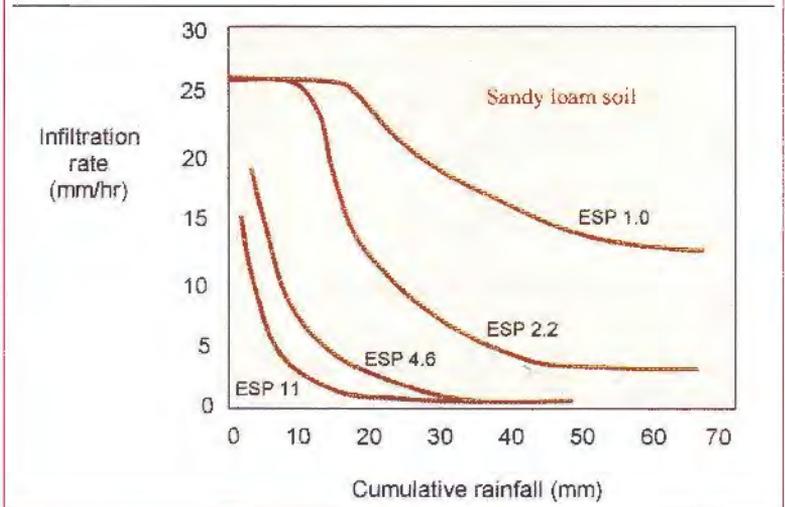


FIGURE 4: Sodic soils can exacerbate waterlogging if the ground has little or no slope.



and causes negligible yield loss. In sodic soils with low CEC, calcium deficiency may be evident, particularly if they are also acid. Calcium deficiency is corrected where lime or gypsum are added as ameliorants.

The sodium itself in sodic soils is not toxic to the crop. Toxicities due to boron, molybdenum, selenium and bicarbonate have been noted in other crops, but do not appear to be a problem in sugarcane.

Roots that are stressed have been shown to be more susceptible to disease and this may also be the case for sugarcane growing in sodic soils. For example, chlorotic streak may cause substantial damage in waterlogged areas and areas with tailwater recycling. Field observations in the Burdekin have suggested that chlorotic streak, waterlogging and tailwater recycling may often be associated with sodic soils (R Schultz, personal communication).

Cultivation and trafficability

Cultivation is most effective and efficient when soil water content is around or just below the plastic limit. If the soil is much wetter when cultivated it smears and if it is much drier, it tends to break up into large clods or pulverise.

The water content range for optimum cultivation is very narrow in sodic soils, so the time period for effective cultivation is shorter than it is for nonsodic soils (Figure 2).

Most soils are prone to compaction when driven on while wet. Sodic soils are particularly prone to compaction due to their low structural stability. They tend to be boggy when wet, making cultivation and harvesting operations difficult.

FIGURE 5: Sodic soils often break up into large clods when cultivated due to their high strength when dry.



FIGURE 6: Sugarcane on sodic soils may show symptoms of water stress only a few days after irrigation or rainfall



Sugar quality

Apart from the agronomic problems associated with sodicity, soils with high clay content and high ESP can cause problems with juice clarification in the mill. Soil inputs to the mill can be higher in sodic soils because they tend to be wetter and boggy at harvest.

In areas where the soils or irrigation water are saline, ash contents in juice are high, causing difficulties in obtaining high quality sugar.

Environmental impacts

The clay that disperses in sodic soils is highly prone to movement in runoff. Under natural vegetation, the soil is usually protected by plants and litter and erosion losses are low. Runoff may be turbid or cloudy for limited lengths of time during high rainfall–runoff events.

However, when sodic soils are cultivated, erosion of clay particles is increased substantially. Under irrigation, tailwater runoff also tends to be turbid. The dispersive nature of sodic clay means that it tends to remain suspended in creeks and wetlands, reducing light penetration and the productivity of submerged aquatic plants.

So the whole ecology of wetlands is upset by the introduction of turbid water from cultivated sodic soils upstream. Clay in runoff water can also increase the amount of nutrients and pesticides moving off the paddock and into waterways, because pesticides and nutrients such as nitrogen and phosphorus are largely bound to clays.

Low yields of sugarcane on sodic soils mean that areas cleared and infrastructure needed for a given level of production are much higher than for more productive soils. ▲

Why do sodic soils behave as they do?

WHAT ARE SODICITY AND SALINITY?

Exchangeable and soluble cations

Clay, because of its small particle size (<0.002 mm in diameter) and large surface area, is the most reactive component of soil. Most types of clay carry a negative charge that is balanced by exchangeable cations (cations are positively charged atoms or molecules). Some types of clay, such as kaolinite, have relatively low amounts of negative charge, while the shrinking–swelling clays, such as montmorillonite, have very high negative charge. Organic matter also carries substantial negative charge.

The amount of negative charge, and therefore the amount of exchangeable cations that a soil can hold, is termed the cation exchange capacity (CEC). CEC is expressed as $\text{cmol}(+)/\text{kg}$ soil (centimoles of charge per kg of soil), which is equivalent to $\text{meq}/100$ g soil (milliequivalents per 100 g soil). The higher the contents of clay and organic matter in soil, the higher the CEC. It ranges from about 1

$\text{cmol}(+)/\text{kg}$ soil in sands to 40 $\text{cmol}(+)/\text{kg}$ soil in heavy clays.

The dominant exchangeable cation in most neutral to alkaline soils is Ca^{2+} . Other cations that can be present in significant amounts are Mg^{2+} , K^+ and Na^+ . Many Australian subsoils have as much or more exchangeable Mg^{2+} than Ca^{2+} . In soils with $\text{pH} < 5.5$, Al^{3+} and H^+ are important exchangeable cations. Above this pH aluminium occurs in different forms that are non-exchangeable.

Exchangeable cations are held close to the soil particles by electrostatic attraction. The higher the charge they have, the more tightly they are held. For example, Al^{3+} is held more tightly than Ca^{2+} , which is held more tightly than Na^+ .

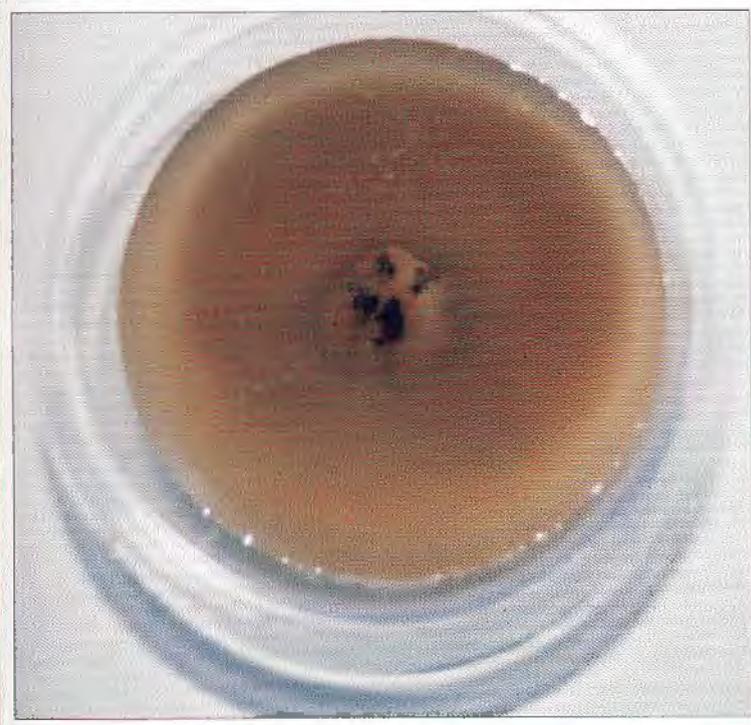
In addition to containing cations attached to the soil particles (exchangeable cations), soils also contain cations, along with anions, in solution. The cations and anions in solution are soluble salts. There is constant exchange between the exchangeable cations and those in solution, so they are said to be in equilibrium with each other. So if there is a high concentration of sodium salts in solution, sodium will also comprise a high proportion of the exchangeable cations attached to soil particles. Adding or removing soluble salts will change the composition of soluble and exchangeable cations in the soil.

Definition of salinity, sodicity and sodic soil

Salinity is the concentration of soluble salts in the soil. Salts are predominantly chlorides, sulfates and bicarbonates of sodium, calcium, magnesium and potassium. In Australian saline soils the most common type of salt is sodium chloride. Saline soils may have any type of texture, but they are normally found in low parts of the landscape where salts have accumulated. Saline soils are not common in wet climates, because the salts are leached out of the profile.

Sodicity is defined as the proportion of the cation exchange capacity of the soil that is taken up by sodium, expressed as the exchangeable sodium percentage (ESP). Thus if a soil has a cation exchange capacity of 12 $\text{cmol}(+)/\text{kg}$ (or $\text{meq}/100\text{g}$), and an

FIGURE 6: When sodic soils become wet, the clay (particles less than 0.002 mm in diameter) disperses. Placing a soil aggregate in distilled water is a good test for soil sodicity, as the dispersed clay moves away from the aggregate.



exchangeable sodium content of 3 cmol(+)/kg, then it has an ESP of 25%. Soils with an ESP > 6 within the A or B horizons are defined as sodic soils and those with ESP > 15 are classed as highly sodic soils. However, there is no particular cutoff value at which soil behaviour deteriorates. The way in which soil behaves at certain values of ESP depends on other soil properties and on how it is managed. The term sodic has replaced the term soda, which referred to alkaline sodic soils.

Salinity and sodicity in soil profiles

Sodic soils usually have a duplex profile, with a light textured topsoil and an abrupt change to a dense clay subsoil (Figure 7). However, soils that have clay texture or lighter texture throughout the profile may also be sodic. In most soils sodicity is greatest in the subsoil, between about 0.3 and 1.0 m depth.

Salinity and sodicity often occur together. Because the dominant type of salt in nature is sodium chloride, and because exchangeable cations are in equilibrium with soluble cations, saline soils are normally also sodic. Soil salinity indicates how leached a soil is — the more leached the soil, the lower the salt concentration. So in wetter climates, or following irrigation with good quality water, soils become less saline, but they may remain sodic. In drier climates, sodic soils tend to be saline, especially at depth.

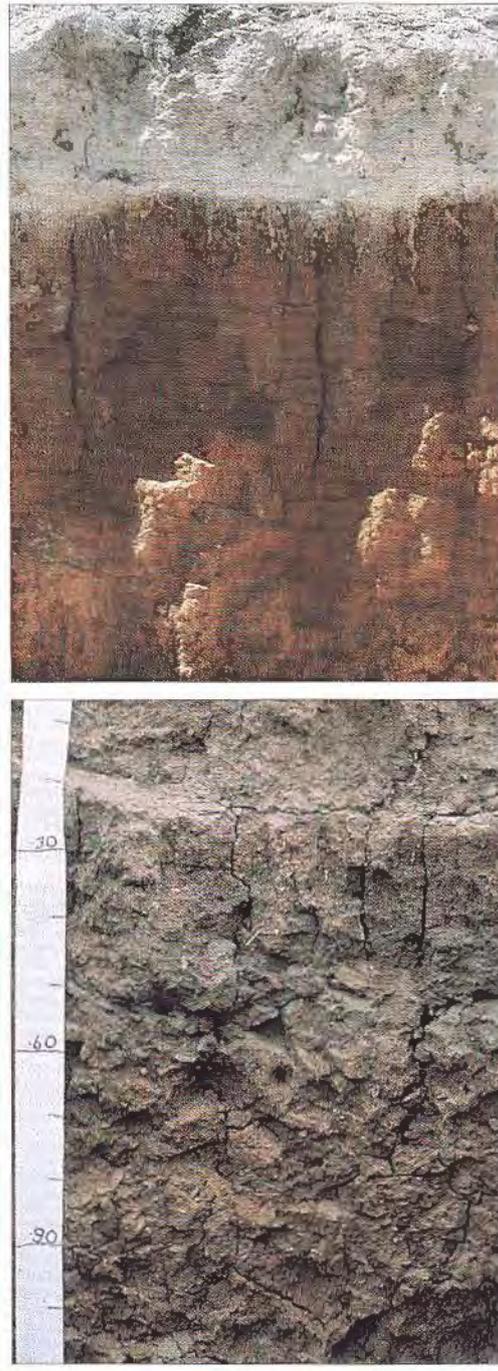
Sodic soils are frequently also alkaline — in other times and places the terms sodic and alkaline have been used interchangeably. The most common pH profile is a slightly acid to neutral topsoil over an alkaline sodic subsoil. Profiles that are alkaline throughout are common in the Burdekin and sodic soils that are acidic throughout the profile are common in the Bundaberg district. Sodic soils also often have relatively high concentrations of magnesium, or high Mg:Ca ratios.

Irrigation water can also be classed as saline when it has a high salt concentration, or sodic when it contains a high proportion of sodium salts.

HOW SODICITY AFFECTS SOIL PHYSICAL PROPERTIES

The physical problems of crusting, poor penetration of water and roots, difficulties in effective cultivation and erosion in sodic soils, are all related to clay dispersion.

FIGURE 7: Two sodic duplex (Sodosol) profiles from the Burdekin (reproduced with permission from Donnollan, 1991).

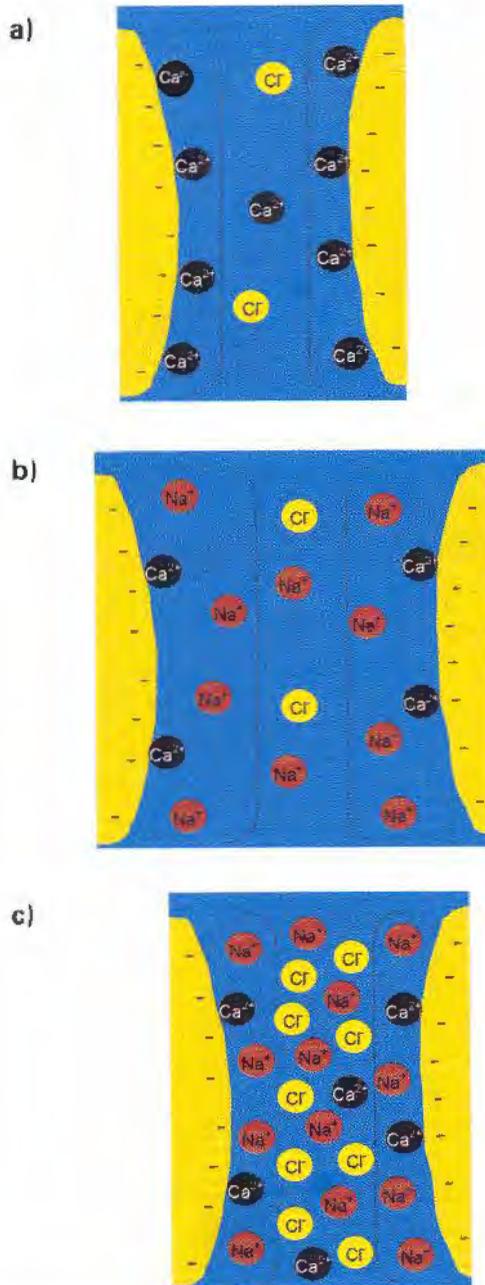


Clay dispersion and soil structure

Exchangeable sodium ions are not very strongly bound to the clay and in a non-saline sodic soil they tend to form a diffuse layer around the clay particles (diffuse double layer).

When the clay particles are free to move in water, they repel each other because of their thick envelope of exchangeable cations. This repulsion causes clay dispersion. In a saline sodic soil, the ions in solution are packed more closely together, and the cations balancing the negative charge on the clay are found closer to the sur-

FIGURE 8: The effects of sodicity at the scale of two clay particles, which are flat and shown in cross section. Each particle is only about 0.01–2 μm in diameter.



a) The dotted line separates the exchangeable cations, which balance the charge on the clay particles, and the soluble cations, whose charge is balanced by anions in solution. When the dominant exchangeable cation is calcium, the layer of exchangeable cations ('double layer' or 'diffuse double layer') is thin, because the calcium ions are bound close to the surface of the particles. The two clay particles normally repel each other, because each is surrounded by a positively charged layer of cations. However, in a non-sodic soil, because the diffuse double layers are thin, the particles can come quite close together. If they come within 0.002 μm of each other, short range attractive forces, similar to gravity, take over, and the particles stick together or flocculate.

b) In a sodic soil, there are more exchangeable cations in the diffuse double layer than in a soil dominated by calcium or magnesium, because the sodium ions have only one charge per ion. Also, because the sodium ions are less highly charged, they are not bound closely to the clay particles. Therefore, the diffuse double layer is thicker than in nonsodic soils, and clay particles cannot approach close enough for attractive forces to dominate. The clay is dispersed.

c) In saline sodic soils, The high concentration of ions forces the sodium ions close to the surface, so the diffuse double layer is compressed, the clay particles can come close together, and flocculation occurs. While the soil remains saline, the clay remains flocculated. However, as soon as the salt is leached out, the clay particles revert back to the situation in b), and dispersion occurs.

faces of the clay particles. The clay particles can move closer together without repelling each other. As they come closer together, attractive forces become stronger. If they move within 0.002 μm of each other, the net force between the particles becomes attractive rather than repulsive, and the particles flocculate. However, if the salt concentration is reduced by leaching, the clay particles disperse (Figure 8).

In nonsodic soils, Ca^{2+} or Al^{3+} are usually the dominant exchangeable cations. Both of these cations have a high charge, so unlike Na^+ , they are bound closely to the clay surfaces. In addition, each Ca^{2+} ion has twice as

much positive charge as each Na^+ ion, so only half as many are required to balance the negative charge on the clay particles. When Al^{3+} or Ca^{2+} are the dominant exchangeable cations the diffuse double layer is thin and the clay particles flocculate.

If clay disperses upon wetting, soil structure is very unstable, and larger aggregates collapse (Figure 9). In highly sodic soils, the wetting action alone is enough to cause structural collapse. In less sodic soils, structure is more stable, but will still collapse if soils are disturbed by raindrop impact, cultivation or compaction. Therefore, stable soil structure is not possible in soils containing dispersive clay.

Interaction of sodicity with other soil properties

Sodicity and salinity are two of the main factors influencing clay dispersion (Figure 10). However, other soil factors such as clay content and clay type, organic matter content, pH and other exchangeable cations also play a role. Good management, particularly minimising disturbance of the soil via cultivation and maximising protection of the soil surface from rain-drop impact reduce clay dispersion at the surface. While flocculated clay is the basis of good soil structure, even if there is no clay dispersion, soil structure and structural stability are not necessarily optimal.

The soil properties mentioned above — particle size distribution or texture, the type of clay, the content of organic matter, pH and management all influence the structure of soils and interact with sodicity.

Texture and clay type

The adverse effects of sodicity are worst in soils with medium texture. In sandy soils, ESP may be high, but the small amount of clay present is not enough to cause sodicity-related problems. So in soils with very low CEC, the ESP value is not particularly meaningful.

At the other extreme, soils with very high clay content tend to shrink and swell. Shrinking and swelling causes cracks and pores to develop, allowing entry of roots and water. Soils with loam to light clay texture tend to have the poorest structure for any given ESP, because they contain enough clay to cause the problems discussed above, but not enough to cause shrinking-swelling behaviour.

Soils with similar proportions of sand, silt and clay are prone to setting hard, even when not particularly sodic, because the particles pack closely together. This is especially the case in soils with high contents of fine sand or silt (Figure 11).

Many Australian soils have hard-setting topsoils due to high contents of fine sand, and poorly-structured subsoils from sodicity.

The type of clay also has an important influence on the behaviour of sodic soils. Soils with a high content of kaolinite clay have low CEC and tend to be fairly stable even if sodic. Kaolinite particles are relatively large and do not shrink and swell when wetted and dried. Kaolinitic soils are often acidic, further decreasing the tendency of clay to disperse. At pH values

FIGURE 9: At the scale of several clay particles, flocculation causes nonsodic clays to form small packets, or microaggregates. Pores form between these packets of clay particles. When the soil dries, these pores lead to cracks forming and a friable structure. In soils containing dispersed clay, the structure is very unstable in water, and no large pores exist. When the soil dries, all the dispersed clay particles come together, and the soil sets hard.

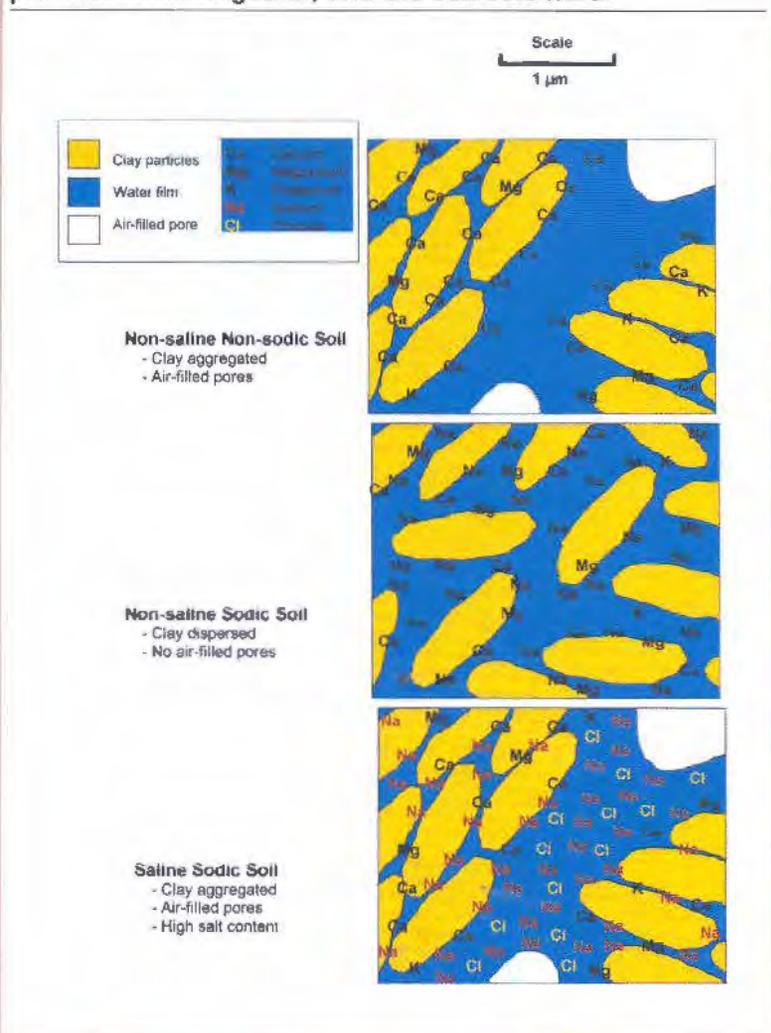


FIGURE 10: Clay dispersion depends on the interaction between sodicity (ESP) and salinity (EC), as shown in this diagram for irrigated Red Brown Earths in Victoria.

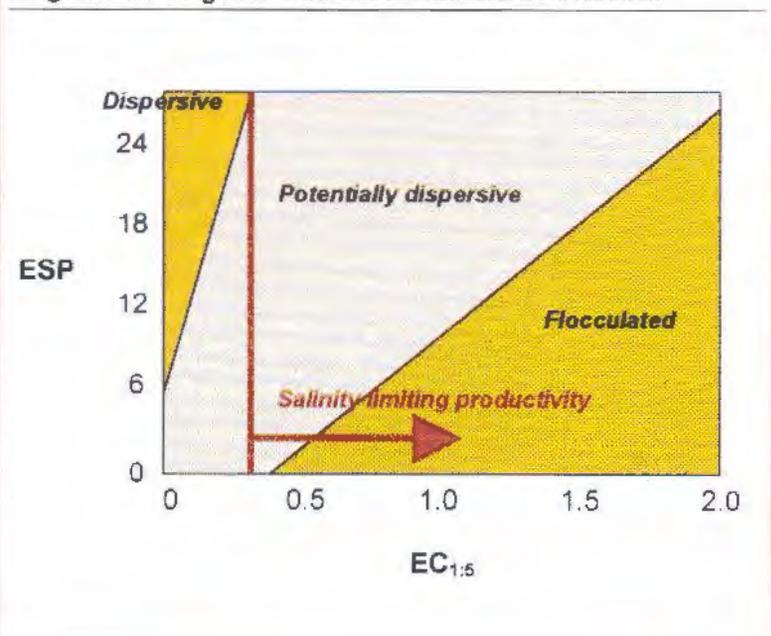


FIGURE 11: Factors other than sodicity influence soil structure, the most important being soil texture and clay type.

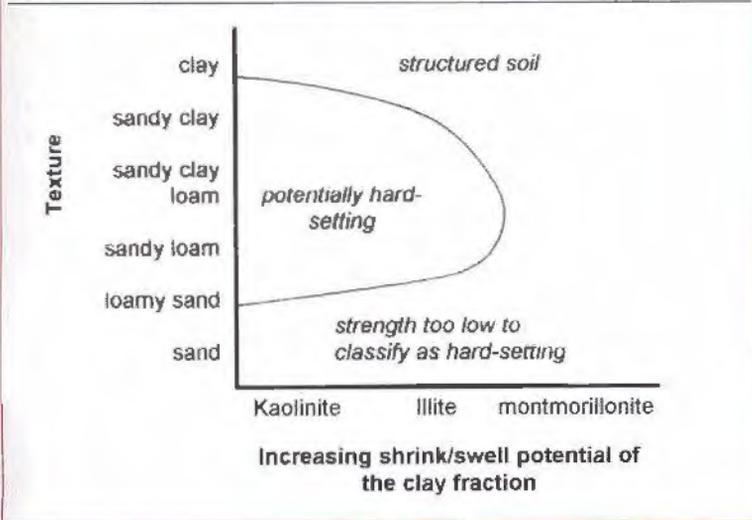


FIGURE 12: The interaction between sodicity and organic matter content is shown by the comparison of water stable aggregation in a soil with different organic matter content due to management (from Barzegar *et al.*, 1997).

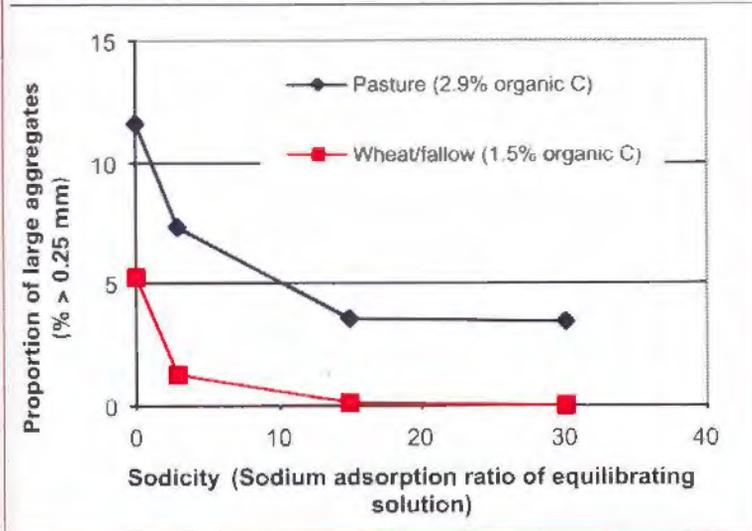
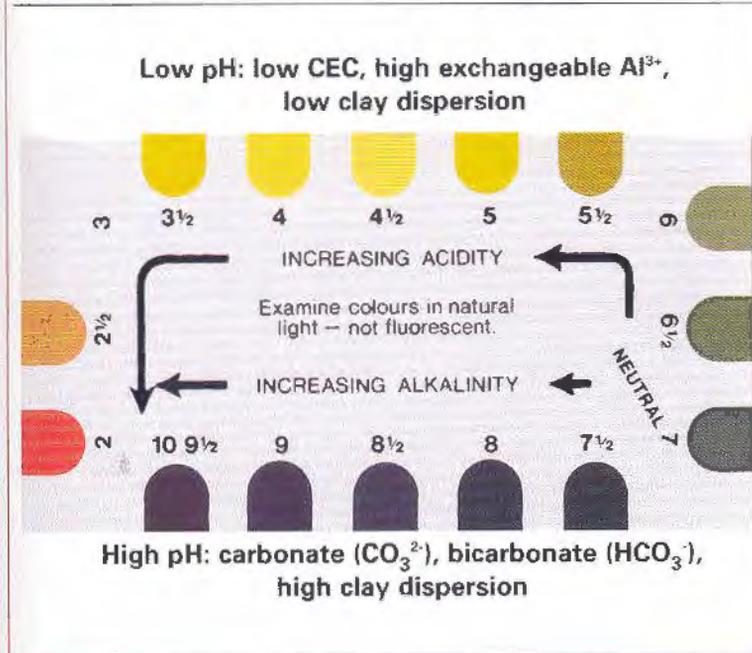


FIGURE 13: Sodic soils with high pH tend to have worse physical problems than sodic soils with low pH.



below 5.5, the amount of exchangeable Al^{3+} becomes high enough to prevent dispersion. Soils with a high content of montmorillonite clays have high CEC and also tend to be reasonably stable when sodic. Montmorillonite clay particles tend to be very small and shrink and swell when wetted and dried.

Soils containing mixed clays and illite clays tend to disperse the most readily when sodic.

Organic matter

Sodic soils tend to have low contents of organic matter due to poor plant productivity, light surface textures and losses through erosion. However, where organic matter levels have been built up by organic matter additions, or growth of vigorous pastures, the plant available water holding capacity and structural stability of sodic soils is improved (Figure 12). Organic matter from plants and microorganisms acts as glue, binding soil aggregates together. However, organic matter is easily lost by decomposition, especially following cultivation, so it must be replenished continually.

pH

Some of the negative charge or CEC in soil is influenced by pH. The higher the pH, the higher the negative charge. In sodic soils this increased charge increases the tendency of clay particles to disperse. pH also influences dispersion through its effect on the solubility of various materials. At high pH, bicarbonate (HCO_3^-) ions react with Ca^{2+} , causing it to precipitate out as $CaCO_3$, in which form it is no longer exchangeable. On the other hand, at low pH, Al^{3+} comes into solution and forms a significant proportion of the exchangeable cations, resulting in flocculation.

Other exchangeable cations

The influence of the cations Al^{3+} , Ca^{2+} and Na^+ on clay dispersion has been discussed above. However, Mg^{2+} is present in significant amounts in many soils, particularly sodic soils and especially in the subsoil. Mg^{2+} is intermediate between Ca^{2+} and Na^+ in its ability to cause clay dispersion. Sodic soils with Mg^{2+} as the dominant cation tend to disperse more readily than those that have Ca^{2+} as the dominant cation. An exchangeable magnesium percentage greater than 20 is generally considered to cause physical problems. ▲

Diagnosis of sodicity and related problems

LABORATORY ANALYSIS AND INTERPRETATION OF TESTS

Decisions on how to manage sodic soils depend on accurate diagnosis of the problems. For example, gypsum response depends on how sodic and saline the soil is. Poor cane growth, poor water penetration, profile characteristics and a knowledge of the area may lead us to suspect sodicity. However, other factors such as salinity, compaction, nutrition and disease may also be involved. For planning sampling and for interpretation of soil tests, *Soil Analysis — an Interpretation Manual* (Peverill *et al.*, 1999) is a useful reference. Other useful materials are produced by fertiliser companies and for the sugar industry (Calcino, 1995).

Representative sampling is essential for meaningful analyses. Poor areas should be delineated. Then 10 or so samples should be taken from within the area and combined for analysis. Where sodicity is suspected, samples should be taken from the 0–250 and 250–500 mm depth layers. Sampling down to 750 mm is worthwhile. Samples should also be taken from adjacent good areas to allow comparison.

Sodicity and related problems are best diagnosed by the measurement of exchangeable sodium percentage (ESP), cation exchange capacity (CEC), electrical conductivity (EC), pH and texture in the

laboratory. Where sodicity is suspected, several soil tests are usually warranted.

Several laboratories do these analyses, including Incitec, Pivot and Mossman Mill.

Cation exchange capacity, exchangeable cations and ESP

Cation exchange capacity (CEC) and exchangeable cations are measured by washing the cations out of the soil using a salt solution and measuring their concentration in the extract. An ammonium (NH_4^+) salt solution is usually used, because ammonium is not present in large amounts in soil.

In most neutral to alkaline soils, Ca^{2+} and Mg^{2+} are the major cations, with smaller amounts of K^+ and Na^+ . In acid soils ($\text{pH} < 6$), Al^{3+} and H^+ can also be present in significant amounts. Therefore, acid soils are usually also extracted with KCl, and the Al^{3+} plus H^+ , or 'exchangeable acidity', in the extract is measured.

The amounts of cations removed in the extracts are added together to determine the CEC. When determined in this way, the CEC is sometimes called the effective CEC or ECEC.

There are other ways of measuring exchangeable cations and CEC, but commercial laboratories use the approach described above.

ESP is calculated by dividing the amount of exchangeable sodium by the CEC and multiplying by 100.

The most commonly-used commercial method uses a fairly concentrated solution of ammonium acetate ($\text{pH} 7$) as the washing solution and treats all soils the same. As saline soils contain significant amounts of soluble sodium salts, the amount of exchangeable sodium is over-estimated by this method. If the soil has been analysed for chloride, the quoted CEC and ESP can be corrected by assuming that all the chloride is associated with soluble sodium (see equation below).

$$\text{Corrected ESP} = 100 \times \frac{b - (a / 355)}{c - (a / 355)}$$

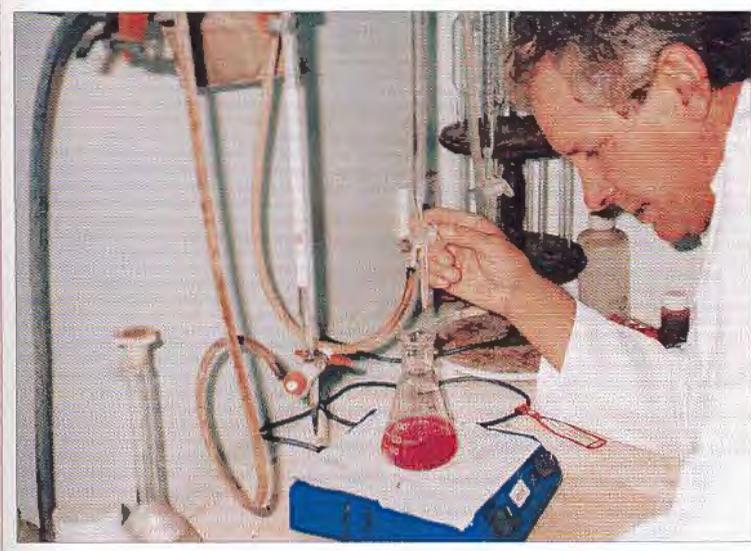
where:

a = chloride content in mg/kg (or ppm)

b = exchangeable sodium content in cmol(+)/kg (or meq %)

c = CEC in cmol(+)/kg (or meq %)

FIGURE 14: Laboratory tests are used to diagnose sodicity and related problems.



For example, a soil has a chloride content of 215 mg/kg, an exchangeable sodium content of 2.9 cmol(+)/kg, and a CEC of 9.8 cmol(+)/kg.

The uncorrected ESP is $2.9 \times 100 / 9.8 = 29.6$.

The corrected ESP = $\frac{100 \times 2.9 - (215 / 355)}{9.8 - (215 / 355)}$

So in this case the corrected ESP = 25.0

Because exchangeable cations are in equilibrium with dissolved cations, soil sodicity may also be assessed by measuring the concentration of cations in the soil solution. When measured in this way, sodicity is expressed as the sodium adsorption ratio (SAR) of the extract (see *Irrigation Water Quality* section for calculation).

The SAR of a saturation extract approximately equals the ESP of the soil. When measured in more dilute extracts (say 1-to-5), the SAR value is lower than the soil ESP.

Salinity

Salinity is measured in the laboratory by measuring the electrical conductivity (EC) of saturation extracts or 1-to-5 extracts (5 ml water for every 1 g soil).

Conversion between these two measurements depends on soil properties, and is discussed in the *Salinity Management Handbook* (1997). Some approximate conversion factors are shown in Table 1.

pH

Soil pH is assessed by measuring the pH of a soil extract. The extract is usually a 1-to-5 extract using water or dilute CaCl₂ solution. A CaCl₂ solution is used to approximate the natural salt concentration in the soil, as salt concentration influences pH. The pH measured in CaCl₂ is usually 0.5–1 units lower than that measured in a water extract.

Texture

Texture, or particle size distribution, can be measured in the laboratory by suspending the soil in water, allowing it to settle, and measuring the amount of particles (by density or by drying and weighing) in the suspension as it settles.

Clay settles very slowly. Sand settles very quickly and is normally measured by sieving the suspension. Due to time and expense of the laboratory method, texture is normally determined by the field or hand method.

Clay minerals

Measurement of the type of clay minerals present is not a routine laboratory test

TABLE 1: Approximate conversion factors between electrical conductivity of a 1:5 soil:water extract (EC_{1:5}) and a saturation extract (EC_e).

Texture	Clay content (%)	To convert EC _{1:5} to EC _e multiply by
Sand, loamy sand, clayey sand	<10	15
Sandy loam, fine sandy loam, light sandy clay loam	10-20	13
Loam, fine sandy loam, silt loam, sandy clay loam	20-30	11
Clay loam, silty clay loam, fine sandy clay loam, sandy clay, silty clay	30-45	9
Medium clay	45-55	8
Heavy clay	>55	6

because of its expense. However, an indication of the predominant type of clay minerals in a soil may be obtained from the ratio of CEC to clay content. CEC (in cmol(+)/kg soil) is divided by clay content (in %) to obtain the soil CEC/clay ratio (CCR, mol(+)/kg clay). The relationship between CCR and clay mineralogy is as follows (Shaw *et al.*, 1998).

< 0.20	kaolinite
0.20–0.35	illite and kaolinite
0.35–0.55	mixed clay mineralogies
0.55–0.75	mixed, with a high proportion of montmorillonite
> 0.75	dominantly montmorillonite

Organic matter

Organic matter content is best measured and expressed in terms of organic carbon content. Multiplying organic carbon content by a factor between 1.72 and 2 gives the approximate organic matter content.

Most commercial laboratories use chemical oxidation procedures to measure organic carbon content. These procedures measure most of the organic carbon. Combustion procedures measure all of the carbon. There are methods that attempt to measure the more active fraction of soil organic matter, but they are used for research rather than routine analysis.

Water retention and hydraulic properties

Analyses of soil physical properties, such as the water retention curve and hydraulic conductivity, may be carried out in the laboratory. However, they are specialised and expensive measurements that are not normally carried out on a routine basis.

Interpretation

Soil test values for ESP should be interpreted in conjunction with the values for texture, CEC, pH and salinity — as discussed above.

DIAGNOSIS IN THE FIELD

While accurate and essential, laboratory analyses have two disadvantages. Firstly, because of their cost, the number of samples analysed from different areas and depths is seldom adequate. Secondly, turn-around time means that immediate results are not possible. Therefore, quick field tests are a useful management tool. A Field Kit has been produced for infield diagnosis of sodicity and related problems in the Australian sugar industry (Nelson, 2000).

The following are some symptoms that may indicate sodicity and salinity, but soils may be sodic or saline without exhibiting many of these characteristics.

Indicators of Sodicity

Original vegetation and weeds

- There are no species that specifically indicate sodic soils. In coastal areas, the following species tend to occur on sodic soils: gum-topped box (*Eucalyptus moluccana*), red ironbark (*E. fibrosa*), narrow-leaved ironbark (*E. crebra*), ironbark (*E. siderophloia*), poplar gum (*E. platyphylla*), messmate (*E. exserta*), ghost gum (*Corymbia papuana*), lemon-scented gum (*C. citriodora*), smooth-barked apple (*Angophora leiocarpa*), prickly-leaved paperbark (*Melaleuca nodosa*), false sandalwood (*Eremophila mitchellii*), broad-leaved banksia (*Banksia robur*), swamp oak (*Casuarina glauca*). In other areas, species associated with sodic soils include beefwood (*Grevillea striata*) in the Burdekin and grader grass (*Themeda quadrivalvis*) in the Mareeba–Dimbulah Irrigation Area.

Crop properties and irrigation problems

- Variations in the height of cane across a block, or yield variations noted at harvest.
- Symptoms of water stress not long after irrigation.
- Poor penetration of irrigation water.

Location and soil properties

- Soil map unit described as sodic (especially in BRIA and MDIA, where soils are mapped at a scale of 1:25,000).

- Soil profile with hard-setting fine sandy loam topsoil, bleached at its base, with an abrupt change to a dense clay subsoil, which may have a domed surface.
- Coarse (> 20 mm) structure, prismatic or columnar structure in the subsoil.
- Surface crusting.
- Dense, hard subsoil (could be any colour).
- Soapy feel when wetting and working up for texture.
- pH > 8.5.
- Cloudy water in puddles.
- Shallow rooting depth.
- Subsoil exposed or brought closer to the surface during levelling.
- Lime nodules in subsoil.

Indicators of Salinity

- Original vegetation and weeds, especially couch grass (*Cynodon* sp) and broad leaf weeds such as button weed (*Epilates australis*) and *Velleia spathulata*.
- Crop properties — symptoms of water stress when soil is wet, tip and leaf margin burn.
- Soil properties — fluffy surface, occasionally whitish salt crusts on top of mounds of aggregates.

Field soil tests

The Field Guide (Nelson, 2000) describes methods for measuring the texture, pH (field method or soil extract), salinity (by EM38 or soil extract EC), dispersibility (Emerson dispersion test) and ESP of soil in the field.

ESP is estimated from salinity, pH, dispersion index, or a combination of EC, pH and sodium concentration, measured in a soil extract. The salinity, sodicity and dispersion hazard of irrigation water may also be measured.

The EM38 meter is an electromagnetic induction meter, which can be used to measure soil salinity in the root-zone. In the vertical mode it measures salinity of the soil down to approximately 1.5 m, and in the horizontal mode it measures salinity down to approximately 0.75 m. It may not pick up high concentrations of salt at very shallow depths. Use of the EM38 in the horizontal mode when held at approximately 50 cm above ground (knee height) improves resolution of shallow depth salinity. ▲

Where do sodic and saline soils occur?

CLASSIFICATION AND MAPPING

In order to map and manage soils, they need to be described and classified in some way. The definition and classification of Australian sodic soils has evolved over time (Isbell, 1995), so a plethora of names exists. Historically, the main classification schemes were the Great Soil Group scheme and the Factual Key scheme. The current and most comprehensive scheme is the Australian Soil Classification. Names for sodic soils in

these classification schemes are shown in Table 2. Many local names are also used.

The Great Soil Group classification scheme, which evolved during the 1930s to the 1960s (Stephens, 1953, 1962; Stace *et al.*, 1968), was the first important scheme, and is still referred to. Of the Great Soil Groups used in the sugar industry, the Solonetz, Solodised Solonetz, Solodic and Soloths were described as being sodic, and the Red Brown Earths and Grey, Brown and Red Clays were described as sometimes being sodic (see *Glossary* for definitions). While the Great Soil Group scheme was widely used, groups were not clearly defined, making it difficult to assign many soils to one of the groups.

The Factual Key (Northcote, 1971) was designed for classification of soils in the field. The main groupings, called Principal Profile Forms, were Uniform, Gradational and Duplex, based on the texture profile (see *Glossary* for definitions). These groups were further divided on characteristics such as pH, colour and structure. For example, a soil with distinct texture contrast between a hard-setting A horizon and yellow clay B horizon, with a bleached A2 horizon and an alkaline reaction trend (profile becoming alkaline with depth), would be classified as a *Dy2.43*. Sodicity was not used in the definitions, but was more-or-less implied through the description of texture and structure.

The Australian Soil Classification (Isbell, 1995, 1996; Isbell *et al.*, 1997) supersedes the previous two schemes. It classifies

FIGURE 15: Typical soil sodicity symptoms — very poor cane growth, waterlogging and grass weed infestation.

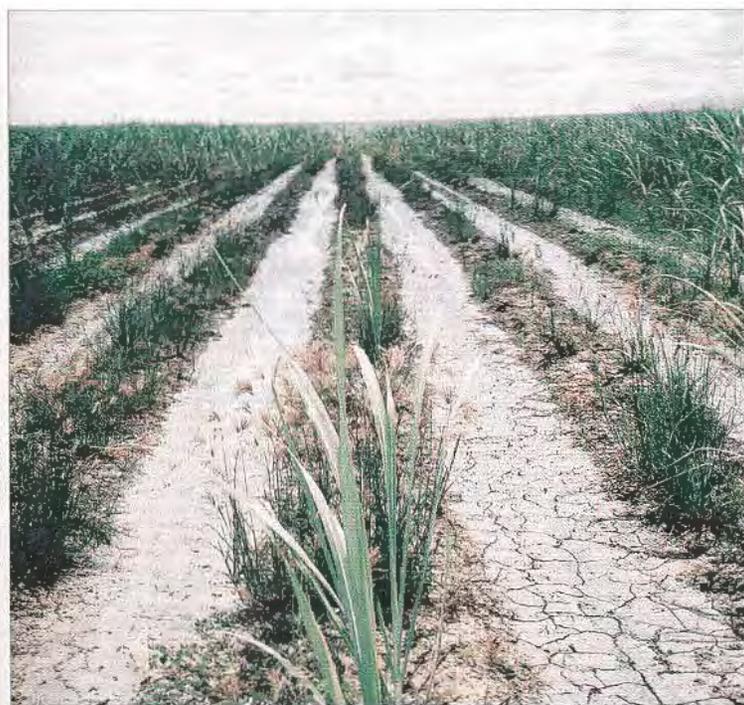


TABLE 2: Some general names used for sodic soils occurring in sugarcane-growing districts in various Australian soil classification schemes. See *Glossary* for definitions of names.

Classification Scheme	Sodic soils	May be sodic
Great Soil Groups (Stephens, 1952, 1953; Stace <i>et al.</i> , 1968)	Solonetz Solodised Solonetz Solodic Soloth (or Solod)	Red-Brown Earth, Grey, Brown and Red Clays
Factual Key (Northcote, 1971)		All Principal Profile Forms of mineral soils, (ie Uniform, Gradational and Duplex, especially Duplex)
Australian Soil Classification (Isbell, 1996)	Sodosol (Texture contrast soil, with top of subsoil having ESP > 6 and pH > 5.5)	Chromosol, Dermosol, Hydrosol, Kandosol, Kurosol, Vertosol (termed Sodic if ESP > 6)

soils into 13 orders and then further divides them according to important and defined characteristics. Sodicty is used at all levels of the classification. One of the orders, the Sodosols, is defined as sodic, having a texture contrast, and an upper B horizon with ESP > 6 and pH > 5.5. Of the other orders, seven (Kurosols, Hydrosols, Chromosols, Dermosols, Kandosols, Calcarosols and Vertosols, see *Glossary* for definitions) are classed as sodic if the A or B horizon has an ESP > 6. All of these orders, with the exception of Calcarosols, occur in the sugar industry.

While soils have been classified using the schemes described above, local names for soil types or soil series are used in each district. These local names are described in the relevant soil maps and reports. The descriptions usually give an indication of sodicty, especially now that the Australian Soil Classification has become standard.

The CRC for Sustainable Sugar Production currently has a project underway to provide soils information for the sugar industry via the world wide web. Meanwhile, maps produced by the Queensland Department of Natural Resources (scales of 1:25,000 to 1:100,000) and reports are available for most cane-growing areas. Relevant maps are mentioned in the following sections.

A list of soil surveys for sugarcane districts of Queensland is included in the *Background Information* section of this manual.

The maps on pages 54–61 show the general distribution of sodic soils in sugarcane districts of Queensland.

ORIGIN AND OCCURRENCE THROUGHOUT THE INDUSTRY

The occurrence and behaviour of sodic soils in Queensland has been discussed by Shaw *et al.* (1995). Sodic and saline soils occur in all sugarcane-growing districts. However, occurrences on the wet tropical coast between Mossman and Tully are confined to small saline areas at the base of the Cassowary Range at Mossman and marine sediments near the coast.

Large areas of sodic soils occur in areas with annual average rainfalls of 1500 mm or less. They tend to be more common in areas developed more recently for sugarcane, because the more productive soils were brought into cultivation earlier.

Sodic soils formed where the concentration of sodium was high in the parent materials. The sodium may have been present as salt, or may have been released during the weathering of minerals. With time and leaching, particularly in wetter climates, the salt is leached out, leaving the soil sodic but not saline. Eventually the exchangeable sodium is also leached out, leaving the soils nonsodic and acidic. Sodic clay also tends to move downwards in the profile, depleting the topsoil of clay and concentrating in the subsoil or further downslope in the landscape.

Sodicty can be quite variable within blocks, and particularly bad areas may occur as small patches. New areas being developed in the Mackay, Proserpine, Burdekin and Atherton Tableland districts contain large areas of naturally sodic soils.

Often land levelling can exacerbate the problem, if highly sodic soil is brought closer to the surface. In some places, soils are becoming sodic under the influence of saline irrigation water and rising groundwater. The problem may only become apparent if a switch is made from saline to good quality irrigation water.

Sodic soils in the sugar industry are generally similar to those found elsewhere in Australia. They tend to have duplex profiles with alkaline, sodic subsoils, often with high exchangeable magnesium percentage and moderately high salinity. However, sodic soils that are acidic throughout the profile are common outside the Burdekin district.

FIGURE 16: Sodicty can be quite variable within blocks, and particularly bad areas may occur as small patches.



Atherton Tableland

Soils of the Mareeba–Dimbulah Irrigation Area (MDIA) are mapped at a scale of 1:50,000 and in some areas 1:25,000.

The Upper Tableland area is dominated by soils of volcanic origin, none of which is sodic. However, soils in the MDIA are far more variable, having developed from a wider range of parent materials of volcanic, igneous and metamorphic origin (Enderlin *et al.*, 2000).

Of the range of soils occurring in the MDIA, those formed on materials of metamorphic origin are the most likely to be sodic. The reason for their sodicity lies with the marine origin of the metamorphosed material that now forms the McLeod Hills and Walsh Bluff Ranges. Erosion of these mountain ranges led to alluvium and colluvium high in sodium and magnesium salts being deposited downslope. Since sodic soils in the MDIA landscape formed from deposited sediments, they occur mainly in the lower parts of the landscape on the tail end of erosion fans, drainage depressions on level alluvial plains and back-plains and floodplains of major and minor streams.

In many locations it is possible to identify a sodic soil deposited on top of another nonsodic soil derived from entirely different parent material. Representative map unit examples are Penman, Penman Sandy, Arriga, Arriga Sandy, Leadingham and Poplar (Enderlin *et al.*, 2000). Sodic soils also develop in situ on the lower to middle slopes of the metamorphic ranges. These soils are generally shallow and overlie weathered mudstone. Representative

map unit examples are Donlen, Mulligan and Masterton (Enderlin *et al.*, 2000).

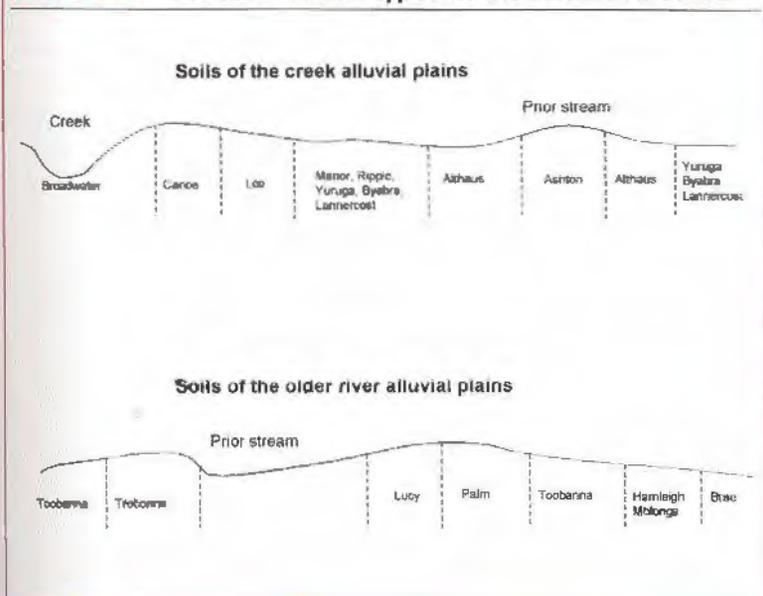
Five map units, Arriga, Arriga Sandy, Donlen, Leadingham and Penman, have been classified as sodic (Enderlin *et al.*, 2000). In the MDIA, the soils represented by these map units make up 15% of the arable land (Class 1–4), and up to 40% of the 7500 ha under sugarcane.

Many, but not all, of these sodic soils are moderately to strongly alkaline at depth. For example, the Arriga and Mulligan soils may be moderately acidic at depth but still reasonably sodic. On the other hand, the Poplar soil is moderately alkaline at depth, but only slightly sodic. However, where there is a strong alkaline reaction trend, this is an unmistakable sign of high sodicity.

Sodicity can vary enormously within short distances. It is fairly common for sodic soils of the MDIA to have high contents of exchangeable magnesium, in some instances up to 90% of the cation exchange capacity.

In the MDIA, natural vegetation is not a reliable indicator of sodic soils. Trees such as poplar gum (*Eucalyptus platyphylla*), box (*Eucalyptus* sp), bloodwood (*Eucalyptus* sp), beefwood (*Grevillea striata*) and tea tree (*Melaleuca* sp) occur across all landscapes. One useful vegetative indicator of sodicity observed in the MDIA is grader grass (*Themeda quadri-valvis*). This grass appears to proliferate to the detriment of all other grass species where moderate to high sodicity levels occur. However, it is also commonly associated with disturbed areas that are not necessarily sodic.

FIGURE 17: Locations of soil types in the Herbert district.



Herbert

All of the Herbert district is covered by DNR soil maps at a scale of 1:100,000. Parts of the district are covered by the 1:5000 CSR soil map, which has an emphasis on the topsoil.

In the Herbert, soils with sodic subsoils are mainly confined to the drier parts of the district, at its western and southern extremes. However, strongly sodic soils do occur in the higher rainfall Seymour and Abergowrie areas. The main landscapes in which they occur are the creek alluvial plains and older river alluvial plains (Wilson and Baker, 1990).

On the creek alluvial plains, sodic soils have finer textures and mainly occur well

away from the sandy prior streams (Figure 17). Both Yuruga and Byabra soils tend to have alkaline sodic subsoils, particularly towards the south-west and south. Drainage is generally poor and the vegetation is dominated by broad leaf tea tree (*Melaleuca viridiflora*) or poplar gum (*Eucalyptus platyphylla*) communities often with scattered ghost gums (*Corymbia papuana*).

Yuruga is a major soil occurring throughout the creek alluvial plains but mainly in the area from Stone River to Yuruga. It has a dark fine sandy surface and a conspicuously bleached A2 horizon with an abrupt change to a mottled yellow-brown or grey medium to heavy clay subsoil. The clay becomes paler and more alkaline at depth. Lime nodules may occur at depth. The Yuruga soil grades into Byabra soil and is associated with Lannercost, which is the acid equivalent. Byabra is a minor soil, similar to Yuruga. Salting has occurred in a small area near Yuruga.

Increasing areas of these soils have been converted from cattle grazing to sugarcane production in the last five to 10 years. Pressure to develop more of these areas is now evident as available land becomes scarce.

On the river alluvial plains, the main soils that can have sodic properties are Toobanna, Hamleigh, Molonga and Brae (Figure 17). Toobanna is one of the major cane-producing soils. It occurs through-

FIGURE 18: Using a soil-coring rig to take soil samples throughout a profile.



TABLE 3: Criteria used in the BRIA to assess the sodicity limitation for sugarcane based on field pH and predicted ESP for Sodosols and Vertosols (Day *et al.*, 1995).

Field pH at 0.3 m depth		Predicted ESP	Yield reduction (%)
Vertosols	Sodosols		
< 8.0	< 6.5	< 6	Negligible
8.0-9.5	6.5-8.0	6-14	10-25
	8.0-8.5	15-25	25-50
	> 8.5	> 25	> 50

out the older river alluvial plains. Its surface is dark fine sandy to clay loam with a conspicuously bleached A2 horizon with a mainly abrupt to clear change to a mottled yellow-brown or brown medium to heavy clay.

The dominance of fine sand in the relatively thick A horizon and the accumulation of manganiferous nodules in the lower A and upper B horizons are characteristic of this soil. Variability in pH occurs towards the south-west, especially in the Stone River area. A dominance of coarse sand in the profile may occur, usually towards the end of prior streams. The vegetation is mainly narrow leaf tea-tree (*Melaleuca dealbata*) woodland to open forest or grassland.

Hamleigh and Molonga are major soils occurring together low in the landscape on the older river alluvial plains. Hamleigh is a dark grey clay with a dark, hard-setting, massive or weakly-structured A1 horizon. A sporadically bleached A2 horizon usually occurs and overlies a mottled, grey, strong blocky, medium to heavy clay. The pH of the subsoil can vary greatly from 5 to 9, but is usually medium acid to neutral. The soil has weak to moderate cracking and occasionally has gilgai development. Molonga is similar except that the A horizon has medium to strong fine blocky structure. Vegetation is mainly grasslands, including blady grass (*Imperata cylindrica*) or open forest of narrow leaf tea-tree.

Brae is a minor soil occurring in swamps in the centre of clay depressions, mainly towards the coast. It is a humic gley with dark humic loam surface and a clear to abrupt change to a mottled dark medium to heavy clay subsoil that becomes paler and more mottled at depth. Brae occurs in association with Hamleigh or Molonga soil types. The vegetation is mainly paper bark tea-tree (*Melaleuca quinquenervia*) open forest to woodland.

Burdekin

Soils of the Burdekin River Irrigation Area (BRIA) have been studied intensively, and are mapped at a scale of 1:25,000. Soils of the Delta are currently being mapped.

Soils of the Burdekin Delta are generally fertile and permeable and include alluvial sands, loams and clays. Most of the soils are not sodic. However, sodic and saline soils do occur, particularly in low-lying areas with marine influences, and under irrigation with saline sodic waters.

The BRIA is predominantly alluvial plains of the Burdekin and Haughton Rivers and local creeks. Sodicity is the most restrictive limitation to growth in the area (Day *et al.*, 1995). A strong relationship between pH and ESP in the area (Baker *et al.*, 1993) has been the basis for predicting ESP and the sodicity limitation for various crops, including sugarcane (Table 3). Soils of the BRIA have been classified into four broad management categories: cracking clays (43% of the area), sodic duplex soils (35%), nonsodic duplex soils (12%) and gradational and uniform noncracking soils (10%) (Donnollan, 1991). Of the surveyed area, 72% is comprised of soils with a sodic B horizon (ESP > 6). Sodic soils fall into three orders, Vertosols, Chromosols and Sodosols (Day *et al.*, 1995).

Vertosols occupy about 34% of the surveyed area in the BRIA. Most have very low slopes and gilgai. Almost all of these Vertosols are sodic by a depth of 0.6 m and strongly sodic (ESP > 15) by 0.9 m. Salinity is low at the surface and moderate by 0.9 m depth. These properties restrict the plant available water holding capacity to < 100–130 mm and plant root-

ing depth to 0.6–0.9 m. Some bleached Chromosols have sodic subsoils, but ESP generally does not exceed 6 until a depth of 1 m.

Sodosols occupy approximately 36% of the surveyed area in the BRIA. They are usually located on slightly elevated, sloping land, just upslope of the Vertosols.

Sodosols of the BRIA have been subdivided into three groups, based on ESP levels at a depth of 0.3 m. The groups are subnatric (ESP 6–14), mesonatric (ESP 15–25) and hypernatric (ESP > 25) at 0.3 m. This depth was chosen because most Sodosols of the BRIA have A horizons less than 0.25 m thick, with a strong texture contrast between the A and B horizons. ESP, pH and electrical conductivity (EC) rise rapidly with depth in these soils, with most

Sodosols having an ESP > 25 by 0.6 m depth. These characteristics of the Sodosols limit plant-available water capacity to 70–95 mm and plant rooting depth to 0.4–0.6 m.

The presence of beefwood (*Grevillea striata*) and false sandalwood (*Eremophila mitchellii*), are commonly associated with strongly sodic soils in the Burdekin.

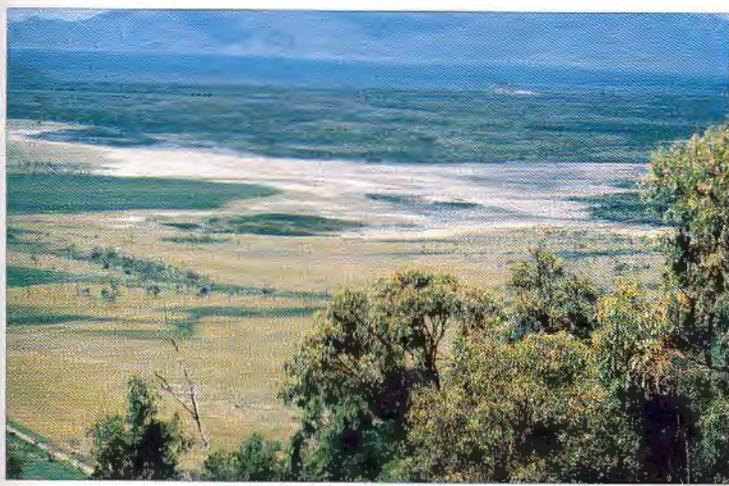
Proserpine and Mackay

In the Mackay district, Land suitability map kits contain soil maps at a scale of 1:50,000. The 1:100,000 soil map of the Plane Creek-Sarina district is currently being improved. In the Proserpine area, mapping, which is being carried out at a scale of 1:50,000, is still underway.

Of the 152,000 ha already mapped in the Proserpine area, 77,900 ha were identified as sodic soils. Approximately 32% of the total cane growing area in the Proserpine area is on sodic soils. This figure is likely to be similar for the Mackay cane growing area. Sodic soils in the Mackay-Proserpine region fall into three broad groups: sodic duplex soils on hillslopes, sodic duplex soils on Quaternary alluvium or recent floodplains and sodic duplex soils on relict floodplains or Cainozoic alluvium.

Sodic duplex soils on hillslopes are formed on volcanic rocks such as rhyolite or acid granites high in sodium feldspar or sandstones and mudstones of marine origin. The sodic duplex soils formed on acid volcanic rock tend to have grey to yellow subsoils and can be acid (Conder and Whiptail soil profile classes) or alkaline

FIGURE 19: As the cane industry expands, more marginal lands, which are often high in sodicity and/or salinity, are being used for cane production.



(Thoopara soil profile class). These soils tend to be shallow to moderately deep.

The Conder soil is classified as a mottled mesonatric to hypernatic Sodosol and the Whiptail and Thoopara soils are mottled subnatric Sodosols. The soils formed on acid volcanic rock tend to be dominated by magnesium and sodium cations causing the subsoil to be dispersive and so is susceptible to erosion. Where the slope is not excessive, some areas of Whiptail and Thoopara are used to grow sugarcane. The vegetation community found on these soils is a Eucalypt open woodland dominated by *Eucalyptus crebra* with a *Melaluca viridiflora* understorey.

Soils formed on acid micro-granites and granites also produce acid sodic duplex soils. The Dunwold soil profile class is a duplex soil with a yellow subsoil with an acid pH. These soils are classified as mottled subnatric Sodosols, though the ESP may increase to 20–30 lower in the profile. Only small areas of Dunwold are used for sugarcane production in the region. The vegetation of Dunwold is similar to that of soils formed on acid volcanic rock.

The Carmilla beds in the region also contain beds of marine deposited sandstones and mudstones. The soils formed on the sandstones can be acid or alkaline. The Pindi and Palmyra soil types are acid sodic duplex soils (mottled subnatric to mesonatric Sodosols).

The Jumper soil profile class is a gravelly, alkaline sodic duplex soil with a yellowish brown subsoil. Where the slope is in general less than 6%, these soils are used for sugarcane production. Small outcrops of marine mudstone occur in the Mackay–Proserpine region. The soils formed on this material tend to be acid. Further analysis of these soils is required to determine whether they contain residual pyrite.

The Proserpine area has soil formed on Tertiary marine sediments. The soils formed from these sediments are mottled subnatric Sodosols with a strongly acid pH trend. The subsoil is a yellowish grey, which descends into the white decomposing shale material. The lower profile has prominent red mottling. When the decomposing material is tested for pyrite using hydrogen peroxide the pH may drop below 3.0. Only very small areas are used for sugarcane production.

Sodic duplex soils on Quaternary alluvium or recent floodplains occur where sodic sediments have been laid down

FIGURE 20: Crusts of dispersed clay can form on sodic soils, especially where the surface has been puddled.



from the surrounding hills. The main alkaline sodic duplex soil types used to grow sugarcane include Sunnyside, Eton, Narpi and Foxdale. These four soils are mainly mottled subnatric Sodosols with the ESP increasing gradually down the profile.

The main acid to neutral sodic duplex soil used to grow cane is Sandiford, which is a mottled subnatric Sodosol with a grey medium clay subsoil. Some of the clay soils formed on Quaternary alluvium are mildly sodic within the upper subsoil (Benholme soil type). Benholme is hard-setting cracking clay formed on floodplains when the catchment is dominated by acid volcanic rocks. The subsoil of Benholme is dominated by magnesium and sodium cations.

The soils formed on Cainozoic alluvium are older and more weathered than those on Quaternary alluvium. They typically have lower Ca:Mg ratios than the Quaternary alluvium (in some cases < 0.1). Some of the soils are underlain by silica pans that harden like sandstone (Koolachu, Slater and Ten Mile soil types). These pans may be centimetres thick to many metres thick. Typically these soils have ESP values between 10 and 35 within the top 10 cm of the subsoil. Both acid and alkaline sodic duplex soils occur.

The most common acid sodic duplex soils are Koolachu and Slater. The Koolachu soil has a loamy sand topsoil over a grey, sandy light to medium heavy clay. The most common Cainozoic alkaline sodic duplex soils are Tailing, Ten Mile and Billy Creek. Approximately 14% of the cane growing area in Proserpine (in 1996) was on these soils. Considerable areas of Cainozoic alluvium, both north and south of Proserpine have been proposed as possible areas for sugarcane expansion.

Bundaberg

Soils of the Bundaberg, Childers and Maryborough areas are mapped at a scale of 1:50,000.

Sodic soils occupy large areas in the Bundaberg–Childers–Maryborough area (Wilson, 1997). In the Bundaberg–Childers area, strongly sodic soils (ESP > 15 in major part of the B horizon) occupy 58% of the total area. However, due to their physical and chemical properties, sodic soils are used less extensively for cropping than other soils. Sodic soils occur in all landscape positions on all types of parent material. However, strongly sodic soils predominately occur in lower slope positions on hillslopes and older parts of the alluvial plains.

Most of the local landscapes have substrates containing sodium feldspars, which weather down to clays containing sodium (eg marine and freshwater sedimentary rocks, rhyolites, andesites, granites, granodiorites). The alluvium derived from these substrates also has similar properties. The movement of sodium in soil water tends to contribute to higher sodicity in lower landscape positions.

The deep weathering (laterised, kaolised, duricrusted) of the local landscapes also contributes to the accumulation of sodium in lower parts of the deeply-weathered profile and lower landscape positions. On fresher or moderately-weathered geolo-

gies, sodic soils generally occur in all landscape positions.

Most sugarcane in the region is grown on landscapes formed from deeply-weathered fine-grained sedimentary rocks. In the upper parts of these landscapes, soils are predominantly permeable, nonsodic soils such as structured gradational Dermosols (Figure 21). Sodic soils occupy lower positions in the landscape.

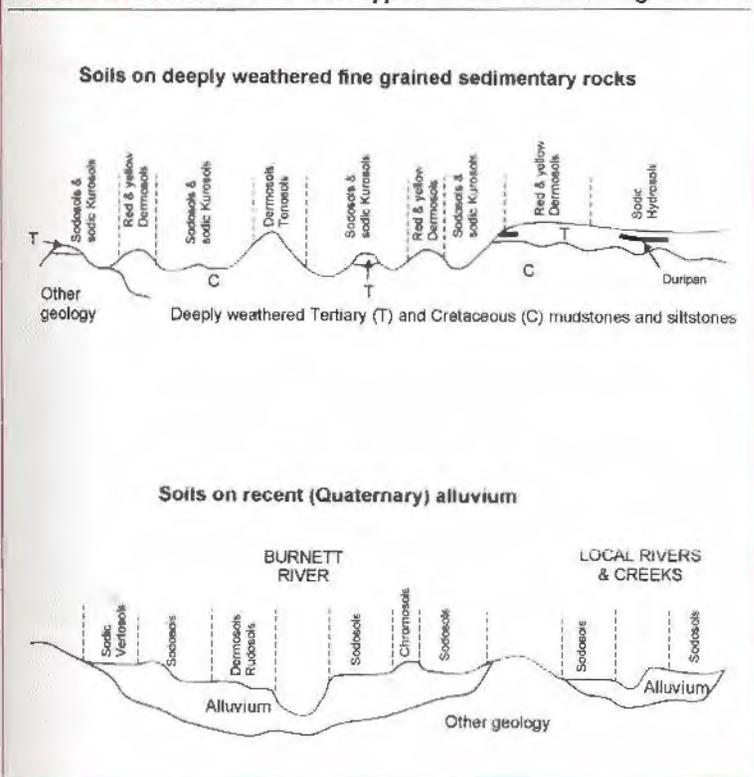
On the agriculturally important alluvial plains (Figure 21), the chemical and physical properties of soils relate to their source of soil-forming minerals and age. The soils around local creeks directly reflect the surrounding geology. The soils of the major rivers (Burnett, Kolan, Mary) reflect the geology in their catchments. For this reason, younger soils on channel benches and younger terraces are generally fertile, lack horizon development and are nonsodic. The older alluvial plains show a high degree of profile development due to weathering of clay forming minerals and/or deposition history. These older soils are always sodic (ESP 6–15) to strongly sodic (ESP > 15).

Most of the strongly sodic soils have a texture contrast profile and strongly bleached A2 horizon. The subsoils tend to have high salinity, 40–50% clay and an intermediate clay activity ratio (0.6–0.8 cmol(+)/kg clay), corresponding to a mixture of montmorillonite–illite–kaolinite clays.

Some of the sodic soils are alkaline, but there are also large areas of acid sodic soils on the deeply weathered landscapes. These soils often have pH values < 5 and high exchangeable acidity and aluminium, which may override the structural instability due to sodium. Mineralogy is often kaolinitic with low cation exchange capacity (and hence low contents of exchangeable sodium) together with cementing agents (oxides of iron, aluminium and silicon), so the dispersive effects of sodicity are poorly expressed. In most of the acid sodic soils, magnesium is the dominant cation and exchangeable calcium contents are very low.

Vegetation on sodic soils tends to include Rusty gum (*Angophora costata*), Spotted gum (*Corymbia citriodora*), Narrow leaf ironbark (*Eucalyptus crebra*), Grey ironbark (*E. drepanophylla*), Broad leaf ironbark (*E. fibrosa*), Gum topped box (*E. moluccana*), Forest red gum (*E. tereticornis*) and tea-trees (*Melaleuca nodosa*, *M. viridiflora*). ▲

FIGURE 21: Locations of soil types in the Bundaberg district.



How should sodic and saline soils be managed?

PRINCIPLES

Management strategies for sodic soils fall into three main categories:

- 1) Avoid cropping sodic soils.
- 2) Reducing sodicity and preventing it from getting worse (Figure 22).
- 3) Managing the soil despite it being sodic.

In reality, most management options involve a combination of two or three of these principles. An essential part of management is to get all the other factors, principally irrigation, nutrition and pest-disease management right. However, it is important to note that factors such as nutrition or varieties cannot compensate for sodicity-related restrictions to growth.

Soils can be made nonsodic by adding a soluble source of calcium such as gypsum, and leaching it through. The calcium replaces the sodium and the leaching water moves the sodium down below the root zone. Gypsum can be applied to the surface of the soil, dissolved in irrigation water, or placed at depth in ripper lines. Unfortunately, complete desodification is normally not economic and sodic soils need to be managed carefully, even if gypsum has been applied. Sodium that has leached below the rootzone may also

move back up again as water is drawn up by evaporation and crop uptake or if the groundwater rises.

Sodic soils have poor structural stability. Management should aim at limiting structural damage and encouraging improvements in structural stability. Structural damage caused by disturbance or compaction can be limited by minimising cultivation and traffic. Structural stability can be improved by maximising inputs of organic matter. Inputs of organic matter are maximised when crop biomass is maximised (by optimising nutrition, weed-disease control, irrigation etc) and by retaining trash.

FARM PLANNING, BLOCK DESIGN AND LEVELLING

The most effective practice for managing sodic soils is to avoid bringing them into production. Soil maps are a valuable resource for farm planning as they indicate soil sodicity. Sodic soils are expensive to develop and provide lower returns than nonsodic soils.

When levelling, it is important not to cut too close to, or to expose layers (scalping) as this will exacerbate the effects of sodicity on growth. Sodic layers should be buried as deep as possible. Soil maps, or analysis during levelling, allows sodicity of various layers to be determined. A nonsodic layer of at least 300 mm depth is preferable. It is possible to apply gypsum to the subsoil following levelling and before the topsoil is replaced.

Where possible, non-sodic soil should be used for top-dressing paddocks and sodic soil should be placed in noncropped areas such as headlands and roads. Nonsodic soil may sometimes be present below sodic layers and can be excavated from recycling pits. Sodic soil makes good headlands and roads when compacted and gently cambered. It does not make good irrigation channels.

An adequate source of good quality irrigation is necessary for amelioration of sodic soils. In furrow-irrigated blocks, arranging the block so that sodic soils are near the top allows them to be irrigated more frequently.

FIGURE 22: Management of sodic soils usually aims at replacing exchangeable sodium with calcium and leaching the sodium below the root zone.

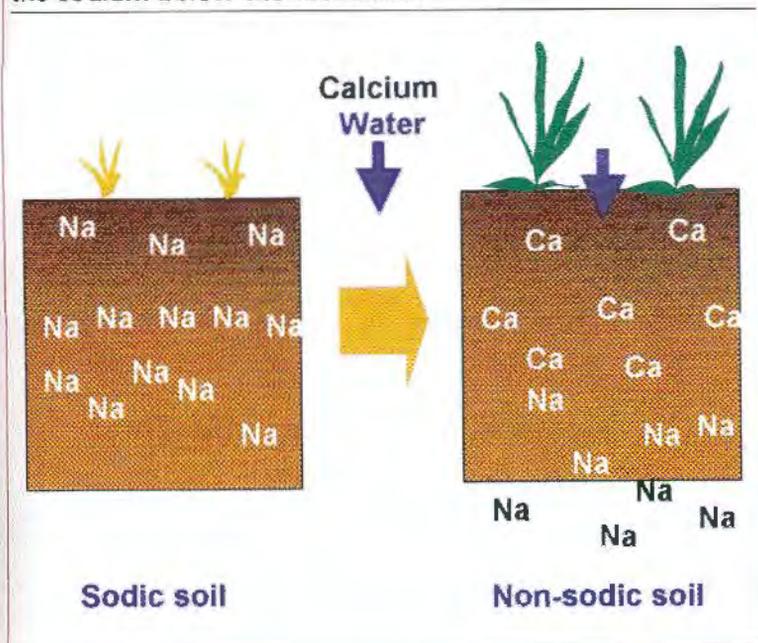


TABLE 4: Cane yield (t/ha) of Q117 on a sodic soil at Gaynor (Burdekin), levelled to different slopes.

Crop class	0.07% slope	0.49% slope
Plant	106	93
1st ratoon	64	50
2nd ratoon	65	52
3rd ratoon	34	21

In areas where groundwater is close to the surface, adequate provision must be made for drains to maintain the water table at more than 1 m below the soil surface. The drainage water must be disposed of in an environmentally acceptable manner.

Water intake is reduced in blocks that have too great a slope. Where water penetration is poor, the slope should not exceed 0.125% or 1:800. Table 4 shows that reducing slope from 0.49% to 0.07% increased cane yield by 24% over a crop cycle in a block with no trash blanket (Ham *et al.*, 1997).

IRRIGATION

Irrigation technique and water quality can be managed to improve water penetration and crop growth on sodic soils. Where the water penetration problem is not severe, it may be overcome by changing the irrigation technique. However, more severe problems will require either a change in the quality of the irrigation water or application of a suitable soil ameliorant.

Irrigation technique

Irrigation methods that apply water frequently in small amounts allow water to

TABLE 5: Effect of irrigation method on cane and sugar yield on a shallow sodic soil in the Burdekin (Ham *et al.*, 1997).

Treatment	Cane yield (t/ha)	Sugar yield (t/ha)
Trickle	116	19.0
Furrow (surge)	113	18.9
Furrow (pea-cup)*	106	17.8
Basin	104	17.4
Furrow	103	17.5
lsd (p = 0.05)	16	2.5

*Allowed to trickle down the furrow for 2-3 days after the normal irrigation

penetrate sodic soils and allow the crop to obtain sufficient water from the less sodic topsoil.

For example, on a shallow sodic soil in the Burdekin, cane tended to yield better under trickle than under furrow irrigation, although results were not significantly different (Table 5).

Under furrow irrigation, water penetration can be greatly improved by forming small hills and making a broad flat interspace. Care should be taken that irrigation water does not simply follow the tractor wheel mark.

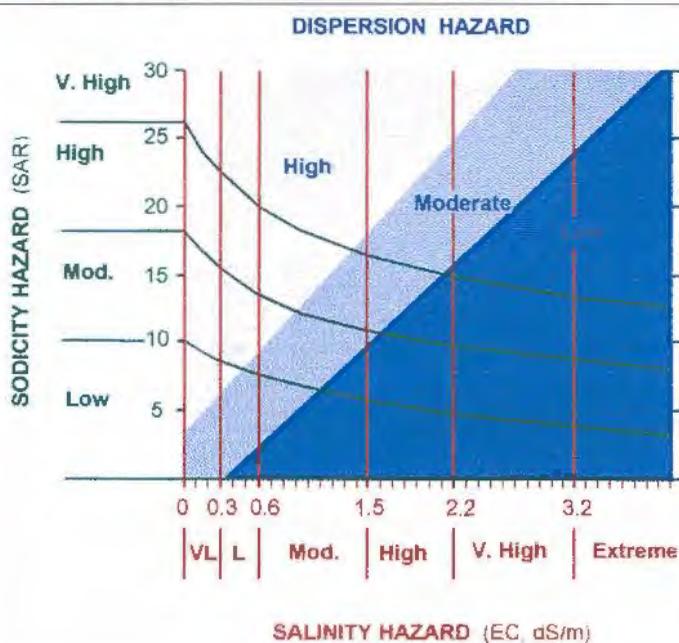
Using small irrigation outlets and larger watering sets will also improve soakage, as do low slopes, discussed above. If sodic soils are situated near the top of the block, it is possible to do short irrigations to the top following the main irrigation.

Tailwater retention has several benefits for managing sodic soils. Overall water use efficiency is greater, salt concentrations tend to increase, leading to better penetration, and the movement of turbid water offsite is reduced.

FIGURE 23: The sodic soil on the left is forming a crust, which reduces infiltration. The same soil on the right, treated with gypsum, is not crusting and is more permeable (photo reproduced with permission from NSW Agriculture *Agfact AC10*, 1996).



FIGURE 24: Dispersion hazard of irrigation water.



Irrigation water quality

The importance of irrigation water quality cannot be overemphasised. The success or failure of many irrigation projects has depended on the quality and subsequent management of irrigation water. Water quality of bores and other sources can vary over time, so samples should be analysed periodically, say once a year. This section explains how waters of different quality should be managed. More detailed information is available in the *Salinity Management Handbook* (1997) produced by the Queensland Department of Natural Resources.

Irrigation waters contain many types of salts. Some are harmful to crop growth while others have beneficial effects. For example, sodium and bicarbonate salts in the water can affect soil structure adversely while calcium salts can improve soil structure. Over time, soils will take on the chemical properties of the irrigation water used on them. Thus without proper leaching, saline soils will result from the use of saline water. Water with a high sodicity hazard will produce sodic soils.

To decide whether an irrigation water is suitable for long term use, a prediction must be made on what the state of the soil will be when it eventually comes into equilibrium with the irrigation water. Water quality and the amount of leaching are the two most important factors to consider in making this prediction.

There are three main hazards that irrigation water can pose to soil behaviour (Figure 24):

- Salinity hazard (measured by electrical conductivity [EC]);
- Sodicity hazard (measured by sodium adsorption ratio [SAR] and residual alkali [RA]); and,
- Dispersion hazard (combination of EC, SAR and RA).

Irrigation waters are classed into one of seven classes based on the dominant hazard or combination of hazards. Each class has different management recommendations. But first each hazard will be described below.

Salinity hazard

Salinity hazard is the risk of accumulating salts in the soil profile. The salinity, or salt concentration, of irrigation water is measured using electrical conductivity (EC). The greater the concentration of salts, the higher the electrical conductivity. The salinity hazard of irrigation water, based on EC, is shown in Figure 24).

The standard EC unit is decisiemens per metre (dS/m). However, conductivity meters commonly read in millisiemens per centimetre (mS/cm) or microsiemens per centimetre (μ S/cm). The scales on the meters are often incorrectly labelled as mS or μ S instead of mS/cm or μ S/cm.

Salinity may also be expressed as mg/L, ppm, or previously as grains per gallon. Units for measuring salinity and electrical conductivity, and conversions between them are shown in the *Units and Conversions* section.

All irrigation waters add salt to the soil. For example 800 mm of water with an EC of 1 dS/m will add about 5 tonnes of salt per hectare. Without adequate leaching, this salt will accumulate in the soil profile. Internal drainage, which is governed largely by texture or clay content, clay mineralogy and sodicity, is necessary for adequate leaching. Ideally, each application of water should leach away the salt left by the previous irrigation. To achieve this, water in excess of the crop's needs must be applied. This excess is known as the leaching requirement. The higher the EC of the water, the greater the leaching requirement. The amount of water applied for leaching will also affect the quality of the resultant drainage water. The less water available for leaching, the more saline the drainage water becomes. The approximate leaching requirements for different irrigation and drainage water qualities are shown in Table 6. In most situations, rainfall can be relied on to provide adequate leaching.

TABLE 6: Long-term irrigation leaching requirements. These values are intended as an indication only, as they also depend on soil properties, climate and crop growth.

EC of irrigation water (dS/m)	Salt added (t/ha per metre of water applied)	Leaching requirement as % of irrigation water to produce drainage water with an EC of:		
		5 dS/m	10 dS/m	15 dS/m
0.1	0.6	2	1	0.7
0.2	1.2	4	2	1
0.4	2.5	8	4	3
0.8	5.0	16	8	5
1.6	10.0	32	16	11
3.2	20.0	64	32	21

The deep drainage that is necessary to prevent salt accumulation in the soil will cause groundwater levels to rise. If the groundwater is not too saline, it may be used for irrigation and this may slow or prevent its rise. If groundwater rises to within 2 m of the soil surface, cane growth will be adversely affected. Subsurface drainage, and disposal of the drainage water is then necessary. Subsurface drainage is discussed below.

Sodicity hazard

Sodicity hazard is the risk that the irrigation water will make the soil more sodic. It is measured by the sodium adsorption ratio (SAR) of the water. The SAR is a measure of the amount of sodium salt as a proportion of all the salts in the water, and is calculated according to the following formula.

$$\text{SAR} = \frac{\text{Na}}{\sqrt{((\text{Ca} + \text{Mg})/2)}}$$

Where Na, Ca and Mg are the concentrations of sodium, calcium and magnesium in mmol(+)/L (or meq/L).

Routine irrigation with water having a given SAR will result in the soil attaining an ESP approximately equal to the SAR of the water. For example, if irrigation water has an SAR of 10, the soil will eventually attain an ESP of approximately 10 in surface horizons. Sodicity hazard is increased by the presence of residual alkali (or free alkali).

Residual alkali (RA) is a measure of the amount of bicarbonate and carbonate ions that are not associated with calcium or magnesium in the water. In the soil, the

TABLE 7: Summary of water quality types.

Type	Quality	Corrective measures
Type 1 EC = 0 – 0.6 dS/m RA = 0 – 0.2 mmol/L	Poor on light soils	May be mixed with gypsum or alternatively treat soil with gypsum or lime
Type 2 EC = 0 – 0.6 dS/m RA = 0.2 – 2.4 mmol/L	Poor on light soils	As above
Type 3 EC = 0.6 – 1.5 dS/m RA = 0 – 0.6 mmol/L	Good	Nil
Type 4 EC = 0.6 – 1.5 dS/m RA = 0.6 – 2.4 mmol/L	Good–fair	Light soils may need gypsum or lime
Type 5 EC = 1.5 – 2.2 dS/m RA = 0 – 2.4 mmol/L	Fair–poor	Ensure irrigation is heavy enough to prevent salt accumulation in the soil. Deep rip.
Type 6 EC = 2.2 – 3.2 dS/m RA = 0 – 2.4 mmol/L	Very poor	Use on sandy soils only. Wet soil to a depth of at least one metre.
Type 7 EC > 3.2 dS/m, or > 2.4 mmol/L	Unsuitable	DO NOT USE

FIGURE 25: Irrigation waters are classified into seven types based on their electrical conductivity and residual alkali content.



bicarbonate ions cause calcium to precipitate out, making it nonexchangeable and so increasing the ESP of the soil. Residual alkali concentration is calculated according to the equation below.

$$\text{Residual alkali} = [\text{HCO}_3^- + \text{CO}_3^{2-}] - [\text{Ca}^{2+} + \text{Mg}^{2+}]$$

Where concentrations are in mmol(+)/L. CO_3^{2-} is generally only present if pH > 9.

Sodicity hazard is also influenced by EC: the higher the EC, the quicker the soil ESP will reach equilibrium with the SAR of the water (Figure 24).

Dispersion hazard

The risk of soil dispersion depends on the EC and SAR of the water, as shown in Figure 24. The risk is greatest with low salinity waters. Dispersion risk also varies according to soil type, especially clay content and type, as discussed in the section on why sodic soils behave as they do.

Water quality types

Irrigation waters have been classified into seven types based on their electrical conductivity and residual alkali content (Table 7).

Type 1: Low salinity waters

When some light-textured soils (eg sandy or silty loams) are irrigated with low salinity water the soil particles disperse and form a slurry, which prevents adequate water penetration.

Type 2: Low salinity waters with dispersion hazard

The presence of residual alkali in this type of water aggravates the penetration problem on light-textured soils. Type 1 and 2 waters are similar in their effect on water penetration and require the same remedial measures.

Type 3: Average salinity waters

Average salinity waters can be used on all soil types. They do not cause water penetration problems or result in excessive build up of soluble salts if leaching occurs.

Type 4: Average salinity waters with dispersion hazard

A moderate amount of soluble salts in the water encourages soil particles to bind together when wet and allows adequate water penetration. However, when the residual alkali content exceeds 0.6 meq/L soil particles may disperse when wet, especially if large amounts of calcium have been removed from the soil. Poor water penetration can then result.

Type 5: High salinity waters

Use of high salinity waters on soils with poor internal drainage will result in a build up of salts in the root zone. This problem occurs mostly with heavy soils or soils having a clay subsoil. With clay soils, water with an electrical conductivity greater than 1.5 dS/m should not be used. On lighter soils, saltier waters may be used.

With high salinity waters, irrigation management is important. Slow, heavy irrigations aimed at leaching salt from the crop root zone must be carried out. Light irrigations will result in a rapid build-up of salt. Deep ripping the soil may improve leaching to below the root zone.

Type 6: Very high salinity waters

Very high salinity waters can be used only on freely-draining sandy soils without causing a serious buildup of salt. Water with a conductivity greater than 3.0 dS/m should be used only in extreme circumstances.

Where Type 6 waters are used, heavy and more frequent irrigations are necessary to leach excess salts from the root zone. Where a buildup of salts is evident, the soil should not be allowed to completely dry out. Drying concentrates salt in the soil solution. During irrigation with these waters, soils should be wet to a depth of at least 1 m.

Type 7: Waters unsuitable for irrigation

Electrical conductivity greater than 3.2 dS/m or SAR greater than 26, or residual alkali greater than 2.4 mmol/L. Such water is not suitable for routine irrigation of sugarcane due to the extreme levels of salt, sodicity or residual alkali.

Other aspects of irrigation water quality

Other important aspects of water quality include the concentration of toxic ions, potential clogging or corrosive materials, and elements required for crop nutrition.

Toxic and other ions

Excessive amounts of chlorine, sodium, boron, lithium and other elements may be toxic to some crops. However, the sodium in sodic and saline irrigation waters is not in itself toxic to sugarcane. High magnesium is a problem in some irrigation water, especially in the Bundaberg district (Skilton *et al.*, 2000). Magnesium affects soil structure in a similar way to sodium, although not as drastically. High magnesium contents can also affect calcium nutrition.

Potential clogging or corrosive materials

The presence of iron, clay or calcium carbonate can cause blockages and shorten the effective life of trickle or spray irrigation systems. Iron is a particular problem in trickle systems. When the irrigation water becomes oxidised or is subjected to pH changes in the system, the iron precipitates out and causes blockages. Acidic waters, especially those with a high proportion of chloride ions, can be very corrosive to irrigation equipment, particularly turbine pumps.

Irrigation water as a source of fertiliser

All irrigation waters contain some potassium, sulfur and traces of zinc. Under full irrigation, sufficient quantities of these elements may be applied to meet the needs of the crop. With full irrigation the amount of potassium and sulfur supplied by irrigation water should be taken into account when deciding on a fertiliser program. The typical amounts involved are discussed in the *Irrigation of Sugarcane* manual (Holden, 1998).

Improving water quality

Dissolvenator

The quality of Type 1 and Type 2 waters may be improved by adding a salt such as

FIGURE 26: All irrigation waters contain some salt.



gypsum (Ham, 1981). The addition of dissolved gypsum to low salinity waters changes these waters to Type 3 irrigation water, suitable for all soil types. Gypsum will also improve Type 4 waters by removing the residual alkali. Increasing the salinity of a Type 4 water may change it to a Type 5 (high salinity water).

A dissolvenator is used to dissolve gypsum in a portion of the water, which is diverted from the main outlet. Once the gypsum has been dissolved this water is mixed with the remaining irrigation water. The percentage of water to be diverted through the dissolvenator depends on its salinity and can be calculated using the equation below or read from Table 8.

$$\begin{aligned} \text{\% of water passed through dissolvenator} \\ = 100 \times (EC_D - EC_I) / 2.1 \end{aligned}$$

Where:

$$\begin{aligned} EC_D &= \text{Desired EC of the mix (dS/m)} \\ EC_I &= \text{Irrigation water EC (dS/m)} \end{aligned}$$

For example, if the EC of the irrigation water is 0.22 dS/m and the desired EC is 0.70 dS/m, then:

$$\begin{aligned} \text{\% of water passed through dissolvenator} \\ = 100 \times (0.7 - 0.22) / 2.1 \\ = 100 \times 0.48 / 2.1 \\ = 23 \end{aligned}$$

Effects of dissolvenator-applied gypsum on cane growth are discussed in the *Ameliorants* section. A general dissolvenator design is given in the appendix (page 62).

Conjunctive use of different water sources

Where several sources of water of differing quality are available, mixing them may improve quality, or allow use of water from a source that would be unsuitable on its own.

TABLE 8: Percentage of water passed through dissolvenator in order to raise EC to 0.7 dS/m.

EC of untreated water (dS/m)	% of water passed through dissolvenator
0.16	29
0.23	25
0.31	21
0.39	17
0.47	12

For example, mixing salty bore water with low salinity channel water may improve soakage and help keep the saline groundwater table well below the surface.

Recycled tailwater may also improve the quality of low salinity channel water. Water from the different sources may be mixed or applied alternately. When mixing, turbulence must be introduced or sufficient length of pipe must be allowed to bring about satisfactory mixing. To determine the feasibility of conjunctive use, the ratio required to attain a given level of salinity can be calculated.

1) The ratio of the mix (R:1, where R is the proportion of the main supply) is calculated as follows:

$$R = \frac{(EC_S - EC_D)}{(EC_D - EC_M)}$$

2) Using the flow rate of the main supply, the flow rate of the supplementary supply can be calculated:

$$Q_S = \frac{Q_M (EC_D - EC_M)}{(EC_S - EC_D)}$$

3) The concentration of any solutes, such as residual alkali, in the mix may be calculated:

$$C_D = \frac{(C_M \times R) + C_S}{R + 1}$$

Where:

C_M = concentration of solute in main supply (any units)

C_S = concentration of solute in supplementary supply (same units as C_M)

C_D = concentration of solute in mix (same units as C_M)

EC_M = EC of main supply (dS/m)

EC_S = EC of supplementary supply (dS/m)

EC_D = desired EC of mix (dS/m)

R = ratio of the mix (R:1, where R is the proportion of the main supply)

Q_M = flow rate of main supply (volume per time in any units, eg L/sec)

Q_S = flow rate required from supplementary supply (same units as Q_M)

For example, if the main source of irrigation water has an EC of 0.18 dS/m, a supplementary supply has an EC of 2.8 dS/m, and the desired EC is 0.7 dS/m, then the ratio of main supply to supplementary supply (R) is:

$$R = \frac{(2.8 - 0.7)}{(0.7 - 0.18)} = 4.0$$

If the flow rate of the main supply is 6 L/s, then the flow rate required of the supplementary supply (Q_S) is:

$$Q_S = \frac{6 (0.7 - 0.18)}{(2.8 - 0.7)} = 1.5 \text{ L/s}$$

If the main supply has a residual alkali content of 0.1 mmol/L and the supplementary supply has a residual alkali content of 2.3 mmol/L, then the concentration of residual alkali in the mix

$$= \frac{(0.1 \times 4.0) + 2.3}{4.0 + 1}$$

$$= 0.54 \text{ mmol/L}$$

In order to calculate the SAR of the mix, the concentrations of sodium and calcium plus magnesium in the mix can be calculated using the third equation above, and then the SAR of the mix calculated according to the equation in the *Sodic Hazard* section.

DRAINAGE

In situations where groundwater is close to the surface, movement of water upwards into the crop and atmosphere during dry periods leaves salts to accumulate in the rootzone. If the amount of effective rainfall plus irrigation water is less than the amount of evapotranspiration, then salts will accumulate in the soil. Therefore, even if the groundwater is not particularly saline, its presence can lead to salinisation and sodification of the soil. Waterlogging due to shallow watertables also decreases crop yields.

The issue of surface and subsurface drainage is dealt with in the BSES booklet *Irrigation of Sugarcane* (Holden, 1998) and the QDNR *Salinity Management Handbook* (1997).

FIGURE 27: Mole drains can form part of a subsurface drainage network, but in sodic soils they clog up rapidly.



TABLE 9: Typical amounts of carbon and nutrients returned in green cane trash in the Herbert (Wood, 1986).

Dry weight (t/ha)	Total C (t/ha)	N (kg/ha)	K (kg/ha)	Ca (kg/ha)	Mg(kg/ha)
16.8	5.4	99	86	47	22

Backhoe pits or bore holes should be dug to determine groundwater levels and the source of the water. Soil surface and groundwater levels are then used to design a drainage system. The heavier textured the soils, the closer together the drains should be.

An EM38 survey can be carried out to determine the extent of salinity in the root zone. An EM31 survey will determine the extent of salinity deeper in the profile. The soil to be drained should be tested for its acid sulfate potential.

The fate of the drainage water should also be considered, as it may have a negative impact on downstream wetlands. It should be kept in mind that drains are not stable in sodic soil, so drainage must be accompanied by amelioration.

Mole drains rapidly clog up in sodic soils, and if used, they should be oriented along the rows so that they can be redone within the crop cycle.

Subsurface drainage is only effective when and where the soil is saturated.

Trash management

Where green cane harvesting is practised, use of a trash blanket improves water penetration. Trash slows the flow of water down the furrow and allows more time for the water to infiltrate into the soil. Increased irrigation times up to 25 per cent have been observed. As the trash breaks down, soil structure at the soil surface is improved and this aids water infiltration. However this effect may be of limited value if soil dispersion still occurs below the surface.

Trash blanketing can benefit management of sodic soils for several reasons:

Mulch effect

By reducing evaporation from the soil surface in young ratoon crops, the amount of water available for plant uptake is increased. On an alluvial soil at Ayr, 60–70 mm more water was conserved under a trash blanket than under a burnt system in the period up till canopy closure. Reduced evaporation loss also means that more water is available for leaching.

Water holding capacity and soil structural stability

Trash blankets hold water, increasing the overall water holding capacity of the soil. Most of the water held in trash is readily available to plants. As trash becomes incorporated into the soil as organic matter by microfauna or cultivation, the readily available water-holding capacity of the soil increases. As microorganisms decompose trash, they produce organic materials that help prevent clay from dispersing, thereby improving soil structural stability at the surface.

Calcium and nutrient supply

The return of nitrogen, phosphorus, sulfur and calcium to the soil is substantially greater with trash retention than with burning. Under a burnt system the nitrogen, phosphorus and sulfur are volatilised and much of the calcium is lost in ash. As trash decomposes, the nitrogen, phosphorus, sulfur and calcium become available. Typical amounts that are returned in a trash blanket are shown in Table 9.

Acidification

Carbon dioxide and organic acids produced during decomposition of trash help to reduce the pH of sodic soils that are alkaline at the soil surface.

Reducing the pH of these soils reduces clay dispersion and helps calcium in applied or naturally occurring lime to dissolve and

FIGURE 28: Where green cane harvesting is practised, use of a trash blanket improves water penetration.



TABLE 10: Cane yields (t/ha) at Gaynor (Burdekin) with and without gypsum addition.

	No gypsum			Gypsum applied (11.25 t/ha)		
	Q96	Q133	Q117	Q96	Q133	Q117
Plant	104	107	106	135	148	148
1st ratoon	61	79	64	80	88	83
2nd ratoon	62	82	65	67	90	83
3rd ratoon	28	39	34	49	58	44

TABLE 11: Soil salinity and sodicity 55 months after gypsum addition (11.25 t/ha) at Gaynor (Burdekin).

Depth	EC1:5 (dS/m)		Chloride (mg/kg)		ESP	
	cont.	+gyp.	cont.	+gyp.	cont.	+gyp.
0.0–0.1 m	0.03	0.08	20	10	9	3
0.2–0.3 m	0.45	0.20	210	30	22	14
1.1–1.2 m	0.69	0.43	1100	150	33	33

Cont. = control, +gyp. = plus gypsum

replace sodium. Carbon dioxide and organic acids are very weak acids and will not cause the pH to drop too low. Leaching is necessary for pH to drop.

AMELIORANTS

The most effective and widely-used ameliorants for sodic soils are those providing a soluble source of calcium. Gypsum and lime are the principal agricultural sources of calcium. The calcium replaces the exchangeable sodium, which is leached down the profile. Amelioration requires the application of sufficient water to leach the sodium below the root zone. Because sodic soils have low permeability, this may take some time. The solubility of sodium salts increases with temperature, so leaching is most effective in the summer.

In order for amelioration to be cost effective, accurate diagnosis is essential. Poor areas should be marked out, then sampled and analysed separately from good areas, so that ameliorant is only applied where needed.

Some incorporation may be desirable to prevent loss from the surface. However, there must be enough ameliorant close to the surface to prevent seal formation. The calcium will eventually move down through the profile if sufficient ameliorant and water has been applied.

Lime or gypsum?

The main difference between lime (CaCO_3) and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is their solubility. When dissolved in water, gypsum attains a maximum EC of approximately 2 dS/m, whereas lime attains a

maximum EC of approximately 0.01–0.40 dS/m. The solubility of gypsum is not influenced by soil pH, whereas that of lime is. Lime is insoluble at $\text{pH} > 8.5$, and becomes more soluble as pH decreases below this value. So while gypsum is an effective source of calcium in all soils, lime is unlikely to have any benefit on sodic soils with pH greater than 7.

Sodic soils with an acid to neutral topsoil and alkaline subsoil, which are quite common, may respond favourably to lime applications. However, as lime is not very soluble, it will not move into the subsoil; gypsum is required for this purpose.

Gypsum

What gypsum is and how it works

Gypsum raises the EC and supplies calcium, which replaces the exchangeable sodium. By these two mechanisms, it reduces clay dispersion.

Gypsum is available in two main forms:

- 1) Byproduct or chemical gypsum, which is a byproduct of the production of phosphorus fertiliser manufacture (also called phosphogypsum) and other industries; and,
- 2) Natural gypsum, which is mined from dune deposits adjacent to evaporite basins.

Phosphogypsum tends to be uniform in quality, have very fine particle size, and dissolve readily. Natural gypsum is more variable in quality and particle size. Larger particle sizes dissolve slowly. The quality of gypsum is defined by its content of calcium and sulfur. Pure gypsum has a calcium content of 23.3% and sulfur content of 18.6%.

Gypsum itself has no significant effect on soil pH. However, in combination with leaching, it can reduce the pH of alkaline sodic soils. Gypsum can be a useful source of sulfur where it is deficient. Every t/ha of gypsum supplies adequate sulfur for five years of sugarcane cropping. Gypsum is the preferred ameliorant for most sodic soils because of its price and solubility. Gypsum is not soluble enough to cause salinity problems, except where it is added to soils that already contain a significant amount of salt.

In order to work, sufficient water must be available to leach the gypsum through the rootzone. As it moves downward, Ca^{2+} replaces exchangeable Na^+ .

Ideally, the displaced Na^+ (moving as NaCl or Na_2SO_4) is leached below the rootzone.

TABLE 12: Cane yield (t/ha) on a sodic soil in the Burdekin.

	Control	Rip.	Diss.	Diss.	Diss.	Sur.	Sur.	Sur.	Isd
				+ rip.	+ rip.	+ rip.	+ mole	+ mole	(5%)
				+ mole					
Plant	50	50	42	46	47	45	48	50	ns
1st ratoon	92	96	115	113	111	109	110	113	11
2nd ratoon	89	93	102	101	103	99	100	105	8
3rd ratoon	80	83	83	92	94	85	85	87	ns

Rip. = ripping, diss. = gypsum through dissolvenator (2 t/ha annually), mole = mole drains, sur. = gypsum applied to the surface (10 t/ha), ns = no significant difference between treatments

TABLE 13: Sugarcane yield (t/ha) in dissolvenator trial at Arriga Park, Atherton Tableland (D. Burgess, personal communication).

Treatment	3rd ratoon	4th ratoon	5th ratoon	Average
		1997	1998	1999
Dissolvenator	119	102 a	105	107.5 a
Dissolvenator + gypsum (5 t/ha)	100	96 ab	100	97.9 b
Gypsum (5 t/ha) + lime (2.5 t/ha)	95	85 bc	89	89.8 c
Gypsum (10 t/ha)	91	87 bc	91	89.7 c
Lime (5 t/ha)	85	83 c	83	83.6 d
Control	86	83 c	89	86.1 cd
Isd (p = 0.05)	ns	12	ns	4.7

However, due to the impermeable nature of sodic subsoils, this process may take some time. If the sodium is not leached sufficiently deep enough, it may move back up into the rootzone as water moves up due to plant uptake and evaporation.

Gypsum rates and responses

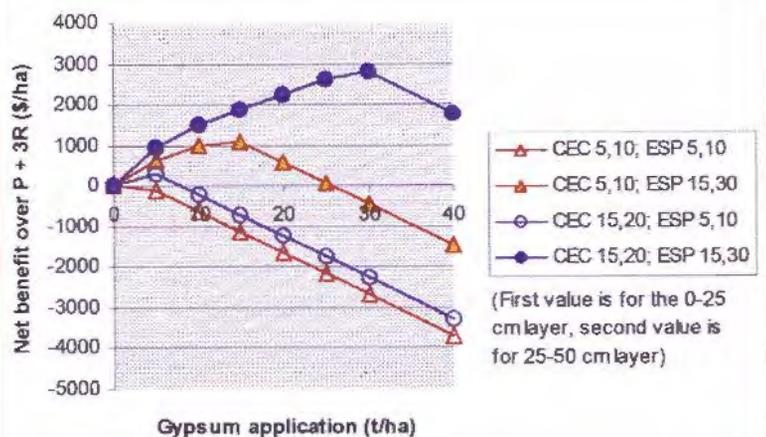
Several trials have shown the effects of gypsum on sugarcane yield on sodic soils. An unreplicated trial on a sodic soil in the Burdekin showed good responses to gypsum (Table 10, Ham *et al*, 1997). Table 11 shows the reduction in soil sodicity under the treatments. Infiltration and the amount of plant-available soil water were also improved.

A subsequent replicated trial on a sodic duplex soil (Dowie series) and cracking clay (Barratta series) showed significant responses to gypsum in the ratoons (Table 12, Ham *et al*, 1997). The plant crop had suffered from prolonged wet weather in all treatments. Gypsum applied through a dissolvenator at 2 t/ha annually gave a similar response to gypsum applied to the surface at 10 t/ha over a crop cycle of plant plus three ratoons. Over the whole crop cycle the costs were similar, but the cost of gypsum applied through the dissolvenator was spread over the whole crop cycle (Ham *et al*, 1997).

A trial in the Mareeba-Dimbulah Irrigation Area (MDIA) showed considerably better

results with dissolvenator rather than surface-applied gypsum (Table 13).

The yield response was sufficient to recover the capital cost of the dissolvenator in two crops over the 50 ha block. The soil had an ESP of 18.4 at 0-25 cm depth and an exchangeable magnesium percentage of 92.4% at 25-50 cm depth.

FIGURE 29: The economic benefit of applying gypsum to sodic soil depends on many factors, including the cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) of the soil.

In this example, the net benefit of adding gypsum to a soil with low or high CEC and low or high ESP has been calculated using the computer program 'Gypsy'. The calculation assumed a nonsaline soil with adequate leaching by rainfall or good irrigation water, a gypsum price of \$85/t, cane price of \$36/t, district being Mareeba or the Burdekin, 7% discount rate and no loss of gypsum in tailwater runoff. Each soil has a different optimum gypsum application rate for the best return.

TABLE 14: The influence of gypsum and lime on cane yields (t/ha) on an acid sodic soil at Proserpine.

	Untreated	Gypsum (10 t/ha)	Lime (2.5 t/ha)	Lime (7.5 t/ha)
Plant	89	108	109	109
1st ratoon	91	98	96	95

Surface application of gypsum provided no additional benefit to the dissolventator treatment. Soil pH was 6.3–6.6 in the top 50 cm, but lime did not improve yield over the control.

Gypsum application rates of 5–10 t/ha are normally recommended for sodic soils. An example of the economics of gypsum applications to soils of various CEC and ESP is shown in Figure 29. The computer program Gypsy (Nelson *et al*, 2000) can be used to estimate the most economic rates of gypsum to apply.

When rates greater than approximately 10 t/ha are indicated, it is suggested that annual rates of 5–10 t/ha be considered, until the predicted rate is reached. On saline sodic soils, lower rates, such as 2–4 t/ha, should be added and salinity monitored. Additional gypsum can be added later.

When sealing of the surface soil is apparent, placement of the gypsum on the surface is a sound strategy. More commonly, it is better to incorporate surface-applied gypsum well into the soil, especially if high rates are involved.

Although no trial data is currently available, application of gypsum to sodic subsoils during levelling is likely to be warranted. However, it would normally still be necessary to apply additional gypsum to the surface after levelling is complete.

Deep ripping, in conjunction with gypsum application, may help the leaching of calcium and sodium through the profile.

Is it possible to add too much gypsum?

Apart from being poor economics, there may be several negative impacts from adding too much gypsum. In soils with low CEC, the cation exchange capacity may become overloaded with calcium at the expense of magnesium and potassium, so resulting in deficiencies of these elements. Kingston (1999) also documented elevated levels of salinity in a low CEC soil over two years following application of 10 t/ha of gypsum. In saline sodic soils, gypsum adds to the salt load of the soil, which may have a detrimental effect on crop growth.

This effect is normally temporary, if sufficient irrigation water is supplied to leach the salts through the profile.

Where large amounts of gypsum are added, the accumulation of contaminants needs to be considered. Contaminants are unlikely to affect sugarcane growth, but may reduce cropping flexibility in the long term, eg cadmium and peanuts.

Lime

Lime is generally defined as a calcium-containing product that increases the pH of soil. Its main purpose is to increase pH and supply calcium in acid soils. It can also be effective in improving the structure of poorly-structured soils, particularly for improving water penetration in soils with low EC. In acid sodic soil, the calcium in lime replaces sodium and reduces sodicity. Anecdotal evidence also suggests that lime may be an effective ameliorant in neutral saline sodic soils.

It may be more effective than gypsum in saline sodic soils because:

- a) Its solubility is increased by the presence of sodium salts; and,
- b) It is not soluble enough to add significantly to the salt load of the soil as gypsum does.

A strip trial on an acid sodic soil (pH 5.5, ESP 33 at 0.25–0.5 m) at Proserpine showed that 2.5 t lime/ha was as effective as 10 t/ha of gypsum (Table 14, Ham *et al.*, 1997).

The term lime normally refers to earth lime or agricultural lime, whose principal ingredient is calcium carbonate (CaCO_3). However, the term lime may also refer to burnt lime, whose principal ingredient is calcium oxide (CaO); slaked lime or hydrated lime, whose principal ingredient is calcium hydroxide (Ca(OH)_2); dolomite (CaMgCO_3); or pulverised lime (usually mostly CaCO_3).

The quality of lime products is usually described in terms of their neutralising value and particle size specifications. Neutralising value quantifies the ability of the product to neutralise acid and is expressed as a percent of the neutralising value of pure calcium carbonate.

Earth lime or calcium carbonate

Calcium carbonate is the cheapest and most commonly used lime product. It is not very soluble, except at low pH or where CO_2 concentrations are high. Smaller particles dissolve more easily

than larger particles. Above pH 8.5 it does not dissolve at all. In dry climates, soils may naturally contain calcium carbonate. Nonsodic soils containing calcium carbonate have pH values around 8.2, whereas sodic or magnesian soils containing calcium carbonate have pH values between 8.5 and 10. Sodic soils that naturally contain more than a few percent of calcium carbonate can be reclaimed by acidification, discussed below. In the sugar industry, some sodic soils contain calcium carbonate, but it usually occurs below the rootzone, and as such it is not useful for reclamation.

Burnt lime or calcium oxide

Calcium oxide is more soluble than calcium carbonate and as such it can be a useful source of calcium. It has a very high pH when it dissolves in water, but when added to soil, the pH usually comes back down to near the original pH. Due to its high pH it can burn setts; it should be incorporated.

Calculating the lime requirement based on soil calcium content

Lime is normally added to correct calcium deficiency and the amount required can be calculated. A calcium content of < 0.55 cmol(+)/kg is considered deficient and 0.55–1.25 cmol(+)/kg is considered marginal. Field trials with fine lime on a range of soils have indicated that the amount of calcium applied approximately equals the increase in exchangeable calcium in the soil one year after amendment application (Kingston and Aitken, 1996).

This relationship can be used to predict:

- (1) The soil's calcium status, using an initial soil test value and a given application of lime; and,
- (2) The amount of lime required to achieve a target soil calcium status.

Example for (1) above:

On the basis of a soil test showing a calcium status (0–25cm depth) of 0.7 cmol(+)/kg a grower applies 5 t lime/ha. The lime contains 38% calcium. Assuming a bulk density of 1.3 t/m³ and that the lime is incorporated into the 0–25 cm depth, the calcium status of the soil after liming is calculated as follows:

*Calcium added = 5000 × 38 / 100 = 1900 kg/ha
Assuming that 80% or 0.8 of this calcium goes onto the exchange capacity (allowing for the fact that ag lime is not as soluble as the fine lime used in the experiments) then:*

Increase in exchangeable calcium =

$$\frac{1900 \times 0.8}{20 \times 1.3 \times 25} = 2.34 \text{ cmol(+)/kg}$$

(The factor of 20 is a constant that accounts for the different units used.)

Soil calcium status after lime application =

$$2.34 + 0.7 = 3.0 \text{ cmol(+)/kg}$$

Example for (2) above:

The same grower with a soil test of 0.6 cmol(+)/kg decides that a soil calcium status of 2.0 cmol(+)/kg would be enough to get through the crop cycle.

How much lime should be applied? The lime available has 38% calcium. Assume a soil bulk density of 1.3 t/m³, that the lime is incorporated into the 0–25cm depth, and that 80% of the applied calcium goes onto the exchange capacity.

Increase in exchangeable calcium =

$$1.4 \text{ cmol(+)/kg}$$

Calcium required =

$$1.4 \times 20 \times 25 \times 1.3 / 0.8 \text{ kg/ha} \\ = 1138 \text{ kg/ha}$$

Lime required =

$$1138 \times 100 / 38 = 2995 \text{ kg/ha} = 3 \text{ t/ha}$$

In acid sodic soils, the increased content of exchangeable calcium is largely at the expense of exchangeable sodium. Therefore, in the example above, if the soil had an exchangeable sodium content of 0.6 cmol(+)/kg, then increasing the calcium status of the soil by 2.3 cmol(+)/kg (example 1, with 5 t/ha lime) or 1.4 cmol(+)/kg (example 2, with 3 t/ha of lime), would both reduce exchangeable sodium content and ESP to zero.

Is it possible to add too much lime?

In soils with low pH buffering capacity, too much lime may increase pH by more than desirable, leading to nutrient deficiencies. Research shows rate of degradation of chlorpyrifos is enhanced at soil pH > 6.2. As this chemical is the mainstay of strategies to manage cane grub populations, it is important that soils should not be limed to pH > 6–6.2 where calcium is required and chlorpyrifos is likely to be applied. Lime and gypsum could be used in such cases to manage both calcium and pH.

Gypsum and lime quality

The quality of gypsum and lime can vary widely. The rules for what products may

TABLE 15: Mean elemental composition of sugar mill byproducts, expressed on a dry weight basis (Barry *et al.*, 1998).

	<i>Mean % composition on dry weight basis (and range)</i>					
	<i>N</i>	<i>P</i>	<i>K</i>	<i>Ca</i>	<i>Mg</i>	<i>S</i>
Filter mud	1.5 (0.8-2.2)	0.9 (0.5-1.4)	0.4 (0.1-0.9)	2.3 (1.4-3.3)	0.6 (0.4-1.1)	0.27 (0.12-0.4)
Mill ash	0.15 (0.1-0.5)	0.17 (0.04-0.3)	0.9 (0.07-2.3)	0.9 (0.2-1.9)	0.7 (0.1-1.1)	0.07 (0.01-0.3)

TABLE 16: Approximate amounts of nutrients supplied by typical applications of mill byproducts (Calcino, 1995).

	<i>Filter mud</i> (150 t/ha)	<i>Mud/ash</i> (150 t/ha)	<i>Ash</i> (150 t/ha)	<i>Molasses</i> after reboiling (10 t/ha)	<i>Liquid dunder</i> (5 m ² /ha)	<i>Biodunder</i> (3 m ² /ha)
N	465	360	60	69	16	24
P	360	300	120	5	1	2
K	120	195	390	397	112	90
Ca	645	600	435	88	17	24
Mg	135	165	225	47	9	18
S	80	50	na	na	13	9

be sold as gypsum or lime — and how they must be labelled — are governed by the Queensland Government Agricultural Standards Regulation (1997). In the legislation, gypsum and lime are classified as fertilisers. Each batch must have a label specifying quality attached to the invoice or delivery docket.

The label must contain the following information: The name and address of the manufacturer or seller; the name, form and content of each main element; and the fineness (< 2 mm for gypsum and < 0.25 mm for lime). Maximum limits have been set for cadmium, mercury and lead contents.

Gypsum must be labelled as one of three grades; third grade if the sulfur content is 10–12.5%, second grade if the sulfur content is 12.5–15%, and first grade if the sulfur content is > 15%.

The sulfur content of pure gypsum is 18.6%. Byproduct gypsum must have > 14% sulfur and a free water content of < 20%.

Gypsum may contain contaminants, which tend to reflect the source. Poor quality mined gypsums may contain a variety of contaminants, including cadmium, arsenic, copper and other heavy metals. The main byproduct gypsum used until recently originated from Incitec phosphate fertiliser manufacture and is high in cadmium.

However, the Duchess phosphate fertiliser plant gypsum, which is likely to become a major source of byproduct gypsum in the near future, has low cadmium content. Byproduct gypsums from metal industries have high concentrations of many heavy metals.

Growers should be aware of contaminants in the gypsum being applied. Ameliorants high in contaminants should be used with caution, as the contaminants may build up in the soil and limit cropping options in the future.

FIGURE 30: The quality of gypsum and lime can vary widely.



TABLE 17: Effect of treatments on bulk density of soil in the 0–10 cm layer, just prior to harvest of first and second ratoon crops (Kingston, 1999).

Treatment	Bulk density (t/m ³)	
	First ratoon	Second ratoon
Trash incorp. + nutrients	1.55 ac	1.54 ab
Trash incorp. + gypsum	1.61 a	1.65 a
Ash	1.41 b	1.47 b
Filter mud/ash	1.42 b	1.50 b
GCTB	1.61 a	1.66 a
Control (trash burnt)	1.52 c	1.58 ab
lsd (* p = 0.05, ** p = 0.10)	0.08 *	0.12 **

Means followed by the same letter are not significantly different

Lime must be labelled with the neutralising value. The neutralising value is the ability of the product to neutralise acid compared to pure calcium carbonate. There is no minimum neutralising value for limes.

Materials such as hydrated lime (calcium hydroxide) or burnt lime (calcium oxide) may have neutralising values greater than 100%. When using lime as a sodic soil ameliorant, the calcium content is more important than the neutralising value. The water content of gypsum and lime can also vary substantially and should be considered.

Mill byproducts

Mill byproducts have been reported to improve production on sodic soils. Their quality varies widely, so the composition of each source should be analysed.

Mill mud increases topsoil depth, has a high content of readily decomposable organic matter, and contains significant amounts of calcium (Tables 15 and 16). Repeated applications can lead to excessive phosphorus levels in soil.

Ash does not contain decomposable organic matter, but at the high rates at which it is applied, its physical properties markedly improve topsoil structure. The main effect is a decrease in bulk density (Table 17). On a severely sodic soil in Mackay, ash reduced ESP in the topsoil, mainly due to the increased concentrations of potassium (Ham *et al*, 1997, Table 18).

Molasses and dunder may also be effective ameliorants for sodic soils because of their high contents of readily decomposable organic matter (Suriadi *et al*, 2000; Weber and van Rooyen, 1971). However, over-application of either will lead to higher ash in sugar related to excessive K uptake.

Acidification of alkaline sodic soils

In alkaline sodic soils (pH > 8.5), Ca²⁺ precipitates out as CaCO₃, and is not available for exchange with Na⁺. Some sodic soils in drier climates contain large amounts of CaCO₃ in the root zone. Soils with more than a few percent CaCO₃ contain more than sufficient calcium for reclamation. The most efficient means of reclaiming these soils is to bring their pH down to < 8.5, so that the CaCO₃ starts to dissolve, and then leach them.

The most common means of acidification is to add sulfuric acid, or elemental sulfur, which is converted to sulfuric acid by soil microorganisms. However, most sodic soils in Queensland do not contain sufficient CaCO₃ in the rootzone for this method of reclamation to be effective.

Acidification from the use of nitrogen fertilisers and buildup of organic matter can help to reduce the pH of alkaline sodic soils,

FIGURE 31: Mill mud increases topsoil depth, has a high content of organic matter and contains significant amounts of calcium.



TABLE 18: Exchangeable cations 26 months after addition of gypsum and ash to a severely sodic soil in Mackay (Ham *et al.*, 1997).

	<i>Control</i>	<i>Gypsum (20 t/ha)</i>	<i>Gypsum + ash (20 + 150 t/ha)</i>	<i>Ash (150 t/ha)</i>
0-250 mm depth				
pH	5.87	5.64	5.65	6.34
EC1:5 (dS/m)	0.02	0.11	0.18	0.09
Ca (cmol+)/kg	1.39	3.55	4.24	1.83
Mg (cmol+)/kg	0.14	0.12	0.17	0.22
K (cmol+)/kg	0.14	0.11	0.2	0.31
Na (cmol+)/kg	0.24	0.11	0.2	0.23
ESP	13	3	4	8
250-500 mm depth				
pH	6.45	6.25	5.88	6.37
EC1:5 (dS/m)	0.09	0.25	0.26	0.13
Ca (cmol+)/kg	1.54	3.1	2.59	1.52
Mg (cmol+)/kg	0.34	0.45	0.44	0.36
K (cmol+)/kg	0.05	0.05	0.05	0.05
Na (cmol+)/kg	2.45	2.06	2.18	2.62
ESP	56	36	40	57

and so reduce clay dispersion and improve soil structure. Anaerobic conditions accelerate this process.

Other ameliorants

Calcium chloride is a very soluble source of calcium. Because of its solubility it can provide rapid amelioration. However, it is very expensive, and needs to be managed carefully because of the salinity problems that can result from its high solubility.

Polymers such as polyacrylamides have been used effectively to stabilise surface soils against dispersion and erosion, or to clarify turbid irrigation water.

VARIETIES AND NUTRITION

All varieties suffer in sodic soils, but more vigorous varieties such as Q124, Q127, Q133 or Q171 are generally the best performers. Normal nutrient management should be carried out in sodic soils, matching nutrient applications to soil test values, and in the case of nitrogen, to projected yield.

CULTIVATION

Minimum tillage and trash retention help to maintain soil structural stability and prevent compaction. Cultivation temporarily improves the structure of sodic soils, but the effect is very short lived as the structure is so unstable when the soil becomes wet.

The costs and negative effects of cultivation, ie accelerated break down of organic

matter and compaction, probably outweigh the benefits in sodic soils, so cultivation should only be carried out when and where necessary.

Under furrow irrigation, cultivation increases the roughness of the soil surface, slowing flow and improving penetration. However, the effect is short-lived as the soil slumps and seals. Likewise, while deep ripping may have a short term benefit by opening up the soil, the effect disappears rapidly when the soil becomes wet. A trial on a sodic soil in the Burdekin showed no significant effect of deep ripping (Table 12). However, farmer experience favours deep ripping in conjunction with gypsum application.

Controlled traffic farming has the potential to improve crop growth on sodic soils, and the current move towards high density planting may facilitate this change. In controlled traffic, wheel traffic is confined to permanent zones, which are allowed to compact. All machinery must have the same, or multiples of the same wheel width. Controlled traffic prevents compaction in the rootzone and promotes better trafficability in the wheeled zone.

In furrow irrigated crops, mound planting is an option to reduce waterlogging damage in flat areas that do not drain readily. However, it should be carried out in conjunction with trash blanketing or cultivation to slow water down in the furrow and encourage soakage into the hill.

MANAGING SALINITY

This manual concentrates on sodicity rather than salinity, but the two are closely related. The QDNR *Salinity Management Handbook* (1997) deals with salinity management. In order to manage soil salinity, the landscape must be understood and the origin of the salt must be known. The salt may originate in the soil itself, from saline irrigation water, or from a shallow groundwater table.

Even if the groundwater is not particularly saline, movement of water upwards by plant uptake and evaporation can concentrate salt in the rootzone. Management should aim at a net movement of salt out of the rootzone (Figure 32).

Irrigation must be carefully managed to prevent soil salinisation. Groundwater must be kept deep enough that water does not move up into the root zone. Management of irrigation and drainage are discussed in the BSES booklet, *Irrigation of Sugarcane* (Holden, 1998) and

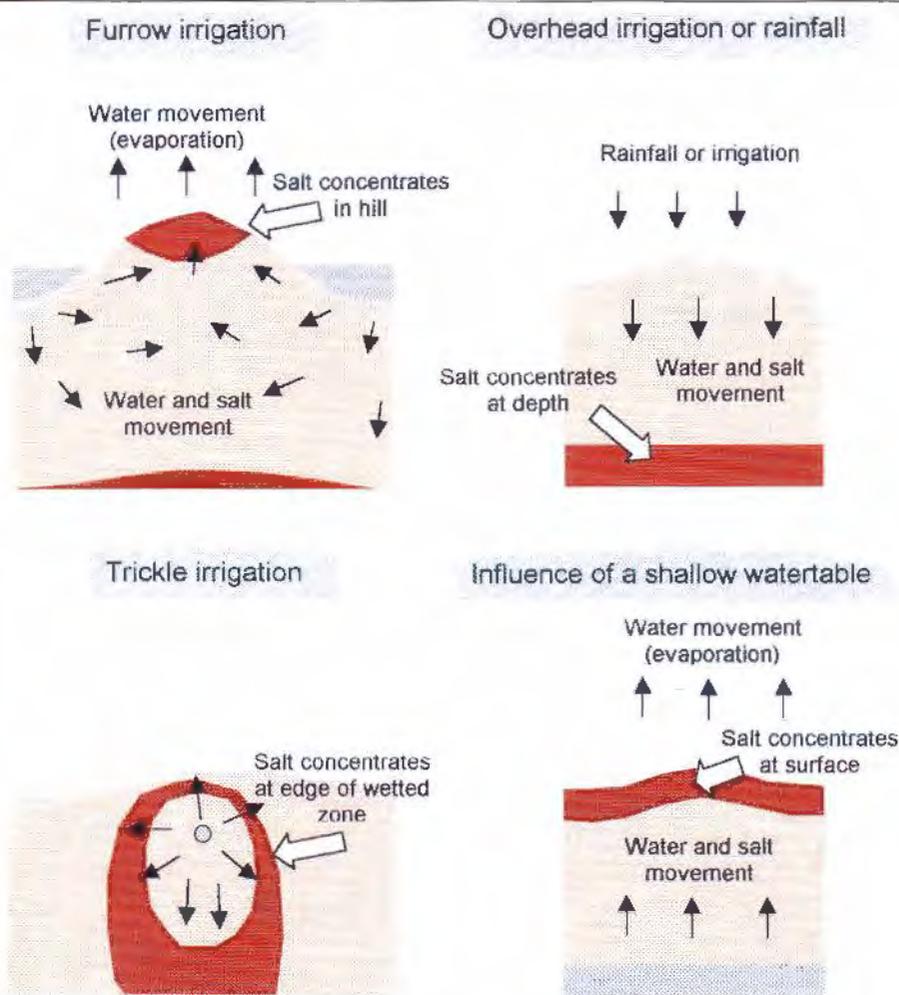
the QDNR *Salinity Management Handbook* (1997). Several computer models (eg HYDRUS, SALF, SWIM and SWAGMAN) are available for determining the movement of salts in soil.

MANAGING WATER PENETRATION PROBLEMS IN NONSODIC SOILS

As discussed in a previous section, non-sodic soils may have poor permeability and crusting or hard-setting behaviour. This is usually due to various combinations of texture (fine sandy or silty loams being the most susceptible), low organic matter content, low electrolyte concentration, mixed clay mineralogy and the soil being in a bare state. Gypsum and lime applications have been shown to increase the EC and improve infiltration in these soils (Ham, 1981).

Trash blanketing and reducing compaction also tend to have beneficial effects. ▲

FIGURE 32: Salt movement.



In all cases, rainfall moves salt downwards, and evaporation moves salt upwards. A net concentration of salt in the root zone must be avoided.

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GLOSSARY AND ABBREVIATIONS

- A horizon** (See HORIZON.)
- Acid** (See pH.)
- Al** (See ALUMINIUM.)
- Alkaline** (See pH.) In the past, sodic soils were often called alkali soils, because many of them have high pH.
- Aluminium (Al)** An element that is a major component of clay minerals in soil. It also exists as a cation (Al^{3+} , $Al(OH)_2^+$, $Al(OH)_2^+$) in acidic soil and water and an anion ($Al(OH)_4^-$) in strongly alkaline soils.
- Ameliorant** Product that, when added to soil, improves soil properties.
- Anion** A negatively charged molecule or element. The most important and abundant anions occurring in soil and water are chloride (Cl^-), sulfate (SO_4^{2-}), carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-). Anions present in small amounts, but which are important for plant nutrition, include hydroxyl (OH^-), nitrate (NO_3^-) and phosphate (PO_4^{2-}).
- Anion exchange capacity (AEC)**
The amount of anions that the soil can hold bound to surfaces of particles. Anions are bound by positive charges on the soil particles, so the AEC is also a measure of the amount of positive charge in the soil. AEC is non-existent in most soils, usually only being significant in the subsoils of deep red volcanic soils. The amount of positive charge in soil increases with decreasing pH. AEC is expressed as $cmol(-)/kg$ soil (millimoles of charge per kg of soil), or $meq/100g$ (milliequivalents per 100g soil). One milliequivalent equals one millimole of charge. AEC can be measured in several ways, all of which involve leaching the soil with a salt solution, and measuring the anions which are displaced. (See CATION EXCHANGE CAPACITY.)
- B** (See BORON.)
- B horizon** (See HORIZON.)
- Bicarbonate (HCO_3^-)** An anion, which exists in alkaline soils and waters. It increases sodicity hazard of irrigation water because it reduces the concentration of calcium, by precipitating it out as calcium carbonate ($CaCO_3$).
- Boron (B)** A trace element, which may exist at concentrations toxic to some crops in some sodic soils.
- BRIA** Burdekin River Irrigation Area
- BSES** Bureau of Sugar Experiment Stations
- Burnt lime** (See LIME.)
- Byproduct gypsum** (See GYPSUM.)
- C** (See CARBON.)
- Ca** (See CALCIUM.)
- Cadmium (Cd)** A trace element, which exists as a contaminant in some byproduct gypsums.
- Calcium (Ca)** An element, which behaves as a cation (Ca^{2+}) in soil and water.
- Carbon (C)** An element, which makes up about 50% of the dry weight of all organic materials, including living organisms. The process of photosynthesis converts C from carbon dioxide into organic forms. (See ORGANIC MATTER.)
- Cation** A positively charged molecule or element. The most important and abundant cations occurring in soil and water are calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+) and in acid soils, aluminium (Al^{3+}). The hydrogen (H^+) is present in small amounts in acid soils, but is important because of its reactivity.
- Cation exchange capacity (CEC)**
The amount of cations that the soil can hold bound to surfaces of particles. Cations are bound by negative charges on the soil particles, so the CEC is also a measure of the amount of negative charge in the soil. Most of the CEC in soil occurs on clay or organic matter. CEC can be measured in several ways, all of which involve leaching the soil with a salt solution, and measuring the cations which are displaced. It ranges from about $1\text{ cmol}(+)/kg$ in sands to about $40\text{ cmol}(+)/kg$ in clays. (See MOLE.)
- CCS** Commercial cane sugar; the recoverable sugar content of cane.
- Cd** (See CADMIUM.)

CEC (See CATION EXCHANGE CAPACITY.)

Centimole (cmol) (See MOLE.)

Chromosol One of the 13 orders of soils in the Australian Soil Classification (Isbell, 1996; Isbell et al., 1997). Chromosols have a strong texture contrast between the A and B horizons, which are not strongly acid (pH < 5.5) and not sodic in their upper 0.2 m. They are termed sodic if they have an ESP of 6 or greater in the lower part of the B horizon.

Clay (See TEXTURE.)

Clay minerals Clay particles in soil consist mostly of clay minerals, as well as some iron oxides, organic matter and other minerals. In soils of the Australian sugar industry there are three main types of clay minerals, each made up of layers of two types of sheets: Si-O tetrahedral sheets and Al-O-OH octahedral sheets. The kaolin type of minerals, of which kaolinite is the most common example, consist of a 1:1 layering of tetrahedral and octahedral sheets. Kaolins do not expand in the presence of water and have low cation exchange capacity (around 5 cmol(+)/kg). Smectites, of which montmorillonite is the most common example, consist of compound layers of tetrahedral-octahedral-tetrahedral sheets (2:1 clays). These compound layers move away from each other in the presence of water, so these clay minerals are called expansible or shrink-swelling. They have high cation exchange capacity (around 100 cmol(+)/kg). Micaceous, often termed illites, are also 2:1 minerals, but the compound layers are bound together by the presence of K⁺. Illites have intermediate cation exchange capacity (around 20 cmol(+)/kg). In soils of the wet tropics, clay mineralogy is dominated by kaolinite and iron oxides, whereas in drier areas illite and montmorillonite are more common.

cmol (See MOLE.)

Conjunctive use of water

Using several (usually two) different sources of water to irrigate the same block. This is done by mixing the two sources or by using them alternately.

Dermosol One of the thirteen orders of soils in the Australian Soil Classification (Isbell, 1996; Isbell et al., 1997). Dermosols lack a clear or abrupt textural B horizon, do not have a free iron oxide content greater than 5% Fe, are not calcareous throughout and have moderately to strongly structured B2 horizons. They are termed Sodic if they have an ESP of 6 or greater in the lower part of the B horizon.

Dispersion Under some conditions, individual clay particles in soil repel each other. When the soil is wet, the particles are free to move away from each other, which causes swelling, and movement of clay into pores. On the surface, dispersion can be seen as cloudiness or turbidity in the water. When the soil dries, all the individual clay particles come together. The pores that remain are too small to readily transmit water or air, and the soil is very hard and dense. The opposite of dispersion is flocculation, where clay particles are attracted together, even in water, to form packets or microaggregates. Because these microaggregates are larger than the individual clay particles, the pores between them are also larger, and a flocculated soil has a soft, permeable, crumbly structure. In most soils clay can be made to disperse by disturbing the soil. In sodic soils, some clay disperses spontaneously. A simple measure of clay dispersibility is described in the *Sodic Soils Field Guide* (Nelson, 2000).

Diffuse double layer (See DOUBLE LAYER.)

Divalent When referring to a cation or anion, it means the ion has two charges (eg Ca²⁺ or SO₄²⁻).

Double layer The layer of exchangeable cations surrounding clay particles. It contains just enough cations to balance the negative charge on the clay particles. Cations within this layer freely exchange with cations in solution, outside of the layer.

Duplex One of the four Principal Profile Forms of the old Factual Key classification of Australian soils (Northcote, 1971). Duplex or texture-contrast profiles are those in which the texture suddenly becomes finer (more clayey) on passing from the A to the B horizon. The term is still commonly used in some local classification schemes. Approximate correspondence between soil groups of the old classification schemes and the new Australian Soil Classification are given by Isbell (1996) and Isbell et al. (1997).

EC (See ELECTRICAL CONDUCTIVITY.)

EC_{1:5} (See ELECTRICAL CONDUCTIVITY.)

EC_e (See ELECTRICAL CONDUCTIVITY.)

Electrical conductivity (EC)

The ability of a material to conduct electricity. The EC of water or a soil extract can be used to estimate its salt concentration. Measuring the EC of soil solution is difficult because of the very small volumes of water that can be extracted from the soil. Therefore, water is normally added to the soil for measurement. Salt tolerance of most plants has been calibrated against the saturation extract EC (EC_e). For soils in Australia, EC is normally measured in a 1:5 soil:water extract (ie 10 g soil plus 50 mL water), giving $EC_{1:5}$. The relationship between $EC_{1:5}$ and EC_e depends mainly on texture, so it is possible to make approximate conversions between the two units (see Table 1). The preferred unit for EC is dS/m (decisiemens per metre), but $\mu\text{S/cm}$ (microsiemens per centimetre), or mS/cm (millisiemens per centimetre) are also commonly used. See *Units and Conversions* section for conversion factors.

Equivalent An equivalent is the old term for a mole of charge. (See MOLE.)

Equivalent weight The 'equivalent weight' of an element (the number of grams per equivalent) is its atomic weight divided by its charge. It equals 23 for Na^+ , 39 for K^+ , 12 for Mg^{2+} and 20 for Ca^{2+} .

ESP (See EXCHANGEABLE SODIUM PERCENTAGE.)

Exchangeable Exchangeable cations or anions are those which can be displaced by leaching the soil with a salt solution. In neutral and alkaline soils, the main exchangeable cations are calcium, magnesium, potassium and sodium. In acid soils, exchangeable aluminium and hydrogen are also important. (See CATION EXCHANGE CAPACITY.)

Exchangeable acidity The amount of exchangeable Al^{3+} plus H^+ in the soil.

Exchangeable sodium percentage (ESP)

A property of soil. The amount of exchangeable Na^+ divided by the cation exchange capacity, multiplied by 100. (See SODICITY and SODIC SOIL.)

Fe (See IRON.)

Flocculation (See DISPERSION.)

Free alkali (See RESIDUAL ALKALI.)

Friable Soil is friable when it easily breaks down into aggregates. (See STRUCTURE.)

Gilgai Small basins and rises that form by shrinking and swelling of clayey soils containing montmorillonite.

Gradational One of the four Principal Profile Forms of the old Factual Key classification of Australian soils (Northcote, 1971). Gradational texture profiles are those in which texture gradually becomes finer (more clayey) with depth. The term is still commonly used in some local classification schemes. Approximate correspondence between soil groups of the old classification schemes and the new Australian Soil Classification are given by Isbell (1996) and Isbell *et al.* (1997).

Grey, Brown and Red Clays

One of the 43 great soil groups of the old Great Soil Group classification of Australian soils (Stephens, 1953, 1962; Stace *et al.*, 1968). Grey, Brown and Red Clays are a broad group defined by high clay content throughout the profile. They may be sodic, especially at depth. (See SOLONETZ, SOLODISED SOLONETZ, SOLODIC, SOLOTH and RED-BROWN EARTHS.) Approximate correspondence between soil groups of the old classification schemes and the new Australian Soil Classification are given by Isbell (1996) and Isbell *et al.* (1997).

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) Gypsum or calcium sulfate is a salt which dissolves fairly easily (although not as easily as sodium chloride). It is therefore a good source of calcium for reclaiming sodic soils or overcoming calcium deficiency, and sulfate for overcoming sulfur deficiency. It is mined or produced as an industrial byproduct, usually the production of phosphate fertilisers.

Horizon Soil layer. The A horizon is the surface layer of mineral soil, usually darkened by organic matter at the top or throughout. It may be divided into sub-layers such as A1 and A2. The term topsoil often more-or-less corresponds with the A horizon. The B horizon is a subsoil layer having concentrations of clay, oxides or organic matter and/or structure and consistence unlike the A horizon above or other layers below and/or stronger colours than the A horizon above or other layers below. The B2 horizon is the sublayer that expresses the B horizon properties most strongly.

Hydrosol One of the 13 orders of soils in the Australian Soil Classification (Isbell, 1996; Isbell *et al.*, 1997). Hydrosols are seasonally or permanently wet soils. They are termed Sodosolic if they fit the definition for Sodosols, and are termed Sodic if they have an ESP of 6 or greater in the lower part of the B horizon.

Hypernatric	(See SODOSOL.)
Illite	(See CLAY MINERALS.)
Ion	(See CATION and ANION.)
Iron (Fe)	An important element in soils, existing mostly as various forms of oxide minerals.
K	(See POTASSIUM.)
Kaolinite	(See CLAY MINERALS.)
Kandosol	One of the 13 orders of soils in the Australian Soil Classification (Isbell, 1996; Isbell <i>et al.</i> , 1997). Kandosols lack a clear or abrupt textural B horizon, are not calcareous throughout, and the clay content of the massive or only weakly structured B2 horizon exceeds 15%. They are termed Sodic if they have an ESP of 6 or greater in the lower part of the B horizon.
Kurosol	One of the 13 orders of soils in the Australian Soil Classification (Isbell, 1996; Isbell <i>et al.</i> , 1997). Kurosols have a clear or abrupt textural B horizon, the upper part of which is strongly acid (pH < 5.5). They are described as Natric (or sodic) if the upper part of the B horizon has an ESP > 6.
Lime	A calcium-containing material that increases the pH of soil. Can refer to a variety of products. See text for more details.
Magnesium (Mg)	An element, which behaves as a cation (Mg ²⁺) in soil and water.
MDIA	Mareeba-Dimbulah Irrigation Area
meq	(See MILLIEQUIVALENT.)
Mesonatric	(See SODOSOL.)
Mg	(See MAGNESIUM.)
Milliequivalent (meq)	A millimole of charge (positive or negative). (See MOLE.)
Millimole (mmol)	(See MOLE.)
mmol	(See MOLE.)
Mo	(See MOLYBDENUM.)
Molybdenum (Mo)	A trace element, which in some sodic soils may exist at concentrations toxic to some crops.
Mole (mol)	A mole is the basic measure of quantity of any element, compound or charge. It contains 6×10^{23} atoms, molecules or charges, respectively. A millimole (mmol) is one thousandth of a mole and a centimole (cmol) is one hundredth of a mole. For example, a cation exchange capacity of one centimole of charge per kilogram of soil (1 cmol(+)/kg) means that there are 6×10^{21} negative charges in each kilogram of soil. For elements or compounds, the number of grams in a mole equals the atomic or molecular weight.
Monovalent	When referring to a cation or anion, it means the ion has one charge (eg Na ⁺ or Cl ⁻).
Montmorillonite	(See CLAY MINERALS.)
N	(See NITROGEN.)
Na	(See SODIUM.)
Neutral	(See pH.)
Nitrogen (N)	An element, which in soils exists mostly in organic form. Apart from carbon, hydrogen and oxygen, it is quantitatively the most important element required by the plant. Sodic soils tend to have low contents of nitrogen because of low organic matter.
Organic matter	Soil organic matter consists of the remains of plants, animals and microorganisms, and also charcoal. The elemental composition of organic matter is generally about 50% C, 1–5% nitrogen, some sulfur and phosphorus, and the rest hydrogen and oxygen. It consists of a wide range of materials, some of which decompose very quickly, others which decompose very slowly. Soil organic matter has many important functions: it provides nutrients for plants; provides energy and nutrients for soil microorganisms and fauna; is an important pool of elements in global cycles; buffers against changes in pH; alters the mobility and reactivity of pollutants and pesticides; and, influences soil physical properties. It has high cation exchange capacity, and can account for a high proportion of the cation exchange capacity of surface soils with low clay content. Organic matter contents can decline quickly under cultivation, and continual returns of plant residues are needed to maintain adequate contents.
P	(See PHOSPHORUS.)

pH The scale of measurement of acidity and alkalinity. A pH of 0–6 is acid, around 7 is neutral, and 8–14 is alkaline. Soil pH can be measured using pH indicator kits (change of colour), or by measuring the pH of a soil extract (water or a CaCl_2 solution) with a pH meter. pH is slightly lower when measured in CaCl_2 than when measured in water. Soil pH varies between approximately 4 and 10.

Phosphogypsum Byproduct gypsum. (See GYPSUM.)

Phosphorus (P) An element, essential for plants.

Plant available water Water in the soil that plants can extract. This is usually described in terms of water potential. At saturation, water is held at approximately zero potential, and is easy for plants to extract (except that they soon become adversely affected by waterlogging, or lack of oxygen). As the soil drains, its water content reaches field capacity, which corresponds to a water potential of approximately -10 kPa, and a maximum water-filled pore diameter of approximately 30 μm . Plants can easily extract this water. As the soil dries further, it becomes increasingly difficult for plants to extract water. At a water potential of approximately -1500 kPa, called the permanent wilting point (maximum water-filled pore diameter of approximately 2 μm), plants can no longer extract water, and they die. The actual water content or amount of water held in soil at different values of potential depends on soil properties, especially clay content. The amount of water held in the soil at field capacity, minus the amount of water held at permanent wilting point, is called the plant available water holding capacity of the soil. The plant available water holding capacity of a soil must specify a depth for which it was calculated, usually the root zone depth. (See READILY AVAILABLE WATER.)

Potassium (K) An element, which behaves as a cation (K^+) in soil and water.

Precipitation A process in which an element or substance is converted from a soluble to an insoluble form.

QDNR Queensland Department of Natural Resources

QDPI Queensland Department of Primary Industries

RA (See RESIDUAL ALKALI.)

Readily available water

Water in the soil that plants can extract easily. The readily available water holding capacity of the soil is the water content at field capacity (for a given depth, usually the rootzone), minus the water content below which plant growth is slowed. The lower limit is determined arbitrarily. For sugarcane it is often set at the water content at which cane growth rate is 50% of the maximum attained. In clay soils, the readily available water holding capacity is often set at 50% of the plant available water holding capacity.

Red-Brown Earth One of the 43 great soil groups of the old Great Soil Group classification of Australian soils (Stephens, 1953, 1962; Stace *et al.*, 1968). Red-Brown Earths have a massive to weakly structured grey-brown to red-brown loamy A horizon, with an abrupt change to a brown to red clay B horizon with well-developed structure. The A horizon is usually slightly acid to neutral, and the B horizons are alkaline, with carbonate segregations in the lower parts. The B horizon is frequently sodic. (See SOLONETZ, SOLODISED SOLONETZ, SOLODIC, SOLOTH and GREY, BROWN AND RED CLAYS.) Approximate correspondence between soil groups of the old classification schemes and the new Australian Soil Classification are given by Isbell (1996) and Isbell *et al.* (1997).

Residual alkali The alkalinity in water (bicarbonate plus carbonate plus hydroxyl, determined by titration) in excess of the amount of calcium and magnesium in water. Free alkali in irrigation water poses a hazard because it complexes calcium, making it nonexchangeable and hence increasing soil ESP.

S (See SULFUR.)

Salinity The salt content of soil or water. The salinity of soil is estimated by measuring the electrical conductivity of soil extracts, or by measuring the electrical conductivity of the whole soil using conductivity probes or an EM38 meter. The salinity of water is estimated by measuring electrical conductivity.

Salinity hazard The salinity of irrigation water, measured by electrical conductivity. The higher the salinity hazard, the greater the risk of salt accumulating in the soil profile.

Salt Material that forms cations and anions when dissolved in water. As salty water conducts electricity, the total salt concentration of water can be measured by its electrical conductivity. Salt concentration in water can be expressed as mg/L (milligrams per litre) or grains per gallon. Salt concentration in soil is often expressed as % (g salt per 100 g soil). See *Units and Conversions* for conversion factors. The most common salt in soil and water in Australia is sodium chloride or table salt (NaCl).

- Sand** (See TEXTURE.)
- SAR** (See SODIUM ADSORPTION RATIO.)
- Saturation extract** (See SOIL EXTRACT.)
- Se** (See SELENIUM.)
- Selenium (Se)** A trace element, which may exist at concentrations toxic to some crops in some sodic soils.
- Si** (See SILICON.)
- Silicon (Si)** An element that is a major component of clay minerals, quartz and other minerals in soil. Small quantities are present in soluble forms.
- Silt** (See TEXTURE.)
- Slaked lime** (See LIME.)
- Soda** (See SODIC SOIL.)
- Sodic soil** A soil that has a high ESP somewhere in the profile. The most commonly used definition is that of Northcote and Skene (1972), who defined a sodic soil as one with an ESP of 6–14 somewhere in the top metre of the profile and a highly sodic soil as one with an ESP > 15 somewhere in the top metre. For more recent and comprehensive definitions of sodic soil, (see SODOSOL, CHROMOSOL, DERMOSOL, HYDROSOL, KANDOSOL, KURO SOL and VERTOSOL.)
- Sodicity** The proportion of the cation exchange capacity of the soil that is balanced by Na⁺. It is usually expressed as the ESP, but may also be expressed as the sodium adsorption ratio of a soil extract. (See SODIC SOIL.)
- Sodicity hazard** A property of irrigation water. The higher the sodicity hazard of irrigation water, the more sodic it will make the soil. Sodicity hazard depends on sodium adsorption ratio, free alkali content and salinity of the water.
- Sodium (Na)** An element, which behaves as a cation (Na⁺) in soil and water.
- Sodium adsorption ratio (SAR)**
A measure of the composition of cations in solution, ie. the concentration of sodium divided by the square root of the concentration of calcium plus magnesium. SAR is used to measure the sodicity of irrigation water.
- Sodosol** One of the 13 orders of soils in the Australian Soil Classification (Isbell, 1996; Isbell *et al.*, 1997). Sodosols are a specific kind of sodic soil, having a clear or abrupt textural B horizon, the upper 0.2 m of which has an ESP of 6 or greater, and a pH of 5.5 or more. Sodosols are divided into three classes depending on the ESP of the upper part of the subsoil: subnatric (ESP 6–14), mesonatric (ESP 15–25), and hypernatric (ESP > 25). Other soil orders used for sugarcane production may also be sodic. (See CHROMOSOL, DERMOSOL, HYDROSOL, KANDOSOL, KURO SOL and VERTOSOL.)
- Soil extract** Soil extracts are used for measuring properties of the soil solution. They are made by mixing soil with water or another solution, and then separating the extract from the soil. Commonly used extracts are the saturation extract and the 1:5 soil:water extract. Saturation extracts are made by wetting the soil up until it is saturated and then removing the extract by vacuum.
- Solodic** One of the 43 great soil groups of the old Great Soil Group classification of Australian soils (Stephens, 1953, 1962; Stace *et al.*, 1968). Solodic soils are the same as Solodized Solonetz, except that their B horizons have coarse blocky structure, without evidence of the characteristic columnar structure. (See SOLONETZ, SOLODISED SOLONETZ, SOLOTH, RED-BROWN EARTH and GREY, BROWN AND RED CLAYS.) Approximate correspondence between soil groups of the old classification schemes and the new Australian Soil Classification are given by Isbell (1996) and Isbell *et al.* (1997).
- Solodised Solonetz** One of the 43 great soil groups of the old Great Soil Group classification of Australian soils (Stephens, 1953, 1962; Stace *et al.*, 1968). Solodised Solonetz soils are similar to Solonetz soils, except that they tend to have a thicker A horizon, with well developed A2 horizon, and the A horizon and upper part of the B horizon is acid. The B horizons have coarse columnar structure with clearly defined domes on top of the columns, and exchangeable sodium contents are less than that of the Solonetz. (See SOLONETZ, SOLODIC, SOLOTH, RED-BROWN EARTH and GREY, BROWN AND RED CLAYS.) Approximate correspondence between soil groups of the old classification schemes and the new Australian Soil Classification are given by Isbell (1996) and Isbell *et al.* (1997).

Solonetz One of the 43 great soil groups of the old Great Soil Group classification of Australian soils (Stephens, 1953, 1962; Stace *et al.*, 1968). The essential features of Solonetz soils are an abrupt texture contrast between loamy A horizons and clay B horizons. The A horizon is fairly thin, has a bleached A2 horizon and has neutral to alkaline pH. The B horizon is strongly alkaline (pH > 9) and exchangeable cations are dominated by sodium and magnesium in the lower part. (See SOLODISED SOLONETZ, SOLODIC, SOLOTH, RED-BROWN EARTH and GREY, BROWN AND RED CLAYS.) Approximate correspondence between soil groups of the old classification schemes and the new Australian Soil Classification are given by Isbell (1996) and Isbell *et al.* (1997).

Soloth One of the 43 great soil groups of the old Great Soil Group classification of Australian soils (Stephens, 1953, 1962; Stace *et al.*, 1968). Soloths are similar to Solonetz, Solodised Solonetz and Solodic soils, except that they are acid throughout the profile. The texture contrast also tends to be less abrupt and the B horizon is not as tough or hard. (See SOLONETZ, SOLODISED SOLONETZ, SOLODIC, RED-BROWN EARTH and GREY, BROWN AND RED CLAYS.) Approximate correspondence between soil groups of the old classification schemes and the new Australian Soil Classification are given by Isbell (1996) and Isbell *et al.* (1997).

Solute Any material that is dissolved.

Structure Soil structure is the arrangement of particles and pores in soil. Soil structure that is optimum for plant growth consists of a range of pore sizes, which allow water, air and roots to penetrate, and which allow the soil to break up easily into aggregates in the size range of mm to cm when it is cultivated. (See STRUCTURAL STABILITY.)

Structural stability The ability of a given soil structure to resist changing when the soil is disturbed by wetting, or by cultivation and traffic. Sodic soils have very low structural stability when they are wet, due to clay dispersion.

Subnatric (See SODOSOL.)

Sulfur (S) An element, which exists mostly in organic form in soil. (See GYPSUM.)

Texture The range of particle sizes of which a soil consists, that is largely responsible for its feel and structure. All soil particles are either clay (0-2 µm diameter), silt (2-20 µm diameter), fine sand (20-200 µm diameter), coarse sand (200-2000 µm diameter) or gravel (> 2000 µm diameter). 'Light' or 'sandy' soils contain a high proportion of sand, whereas 'heavy' or 'clayey' soils contain a high proportion of clay. Loams generally contain 10-40% clay, with the rest being silt and sand. Texture can be measured in the field by feel, or in the laboratory by particle size analysis.

Trace element An element that exists in low concentrations in soils or amendments. Concentrations in soils may be too low (deficient) or too high (toxic) for plants.

Uniform One of the four Principal Profile Forms of the old Factual Key classification of Australian soils (Northcote, 1971). Uniform texture profiles are those in which there is little, if any, change in texture throughout the profile. Uniform profiles may be coarse (sandy), medium (loamy) or fine (clayey) texture. The term is still commonly used in some local classification schemes. Approximate correspondence between soil groups of the old classification schemes and the new Australian Soil Classification are given by Isbell (1996) and Isbell *et al.* (1997).

Vertosol One of the thirteen orders of soils in the Australian Soil Classification (Isbell, 1996; Isbell *et al.*, 1997). Vertosols have 35% or more clay throughout the profile. They are termed Episodic if they have an ESP of 6 or greater in the upper 0.1 m, Epihypersodic if ESP is 15 or greater in the upper 0.5 m and Endohypersodic if ESP is 15 or greater below 0.5 m.

Water potential The energy with which water is held in the soil. Within a certain range it can be measured directly by tensiometers. It is usually expressed in units of pressure, such as bar or kPa (1 bar = 100 kPa). Water that is held at a potential of between zero and say -10 kPa can be extracted from soil by applying a pressure of 10 kPa. Water that is held at a potential of -1000 kPa can only be extracted by applying a pressure of 1000 kPa. The smaller the pores in which water is held, the more negative its potential, and the more difficult it is for plants to extract. (See PLANT AVAILABLE WATER.)

Zinc (Zn) A trace element, which in some sodic soils may exist in concentrations deficient for some crops.

Zn (See ZINC.)

Units and conversions

To convert Column 1 into Column 2 multiply by: *To convert Column 2 into Column 1 multiply by:*

Salt concentration and electrical conductivity of water and soil extracts*

1000	dS/m	µS/cm	0.001
1	dS/m	mS/cm	1
1	dS/m	mmho/cm	1
1	mmolc/L	meq/L	1
0.1 (approx.)	mmolc/L	dS/m	10 (approx.)
600 (approx.)	dS/m	mg/L	0.0017 (approx.)
1	mg/L	ppm	1
45 (approx.)	dS/m	Grains per gallon	0.022 (approx.)
0.07	mg/L	Grains per gallon	14.3
1	µS/cm	'EC units'	1

Cation exchange capacity and concentrations in soil

1	cmol(+)/kg	me %	1
1	cmol(+)/kg	meq/100 g	1
1	meq/100 g	me %	1
1	mg/kg	ppm	1
0.1	mg/kg	%	10
0.1 x equiv. weight	mg/kg	cmol(+)/kg	10 x equiv. weight

Application rates

0.008	kg/ha	bags/acre	125
0.398	t/ha	t/acre	2.51

Flow rates, irrigation applications

3.6	L/sec	kL/hr	0.278
793	L/sec	gallons/hr	0.0013
0.01	mm	ML/ha	100

Slopes

To convert percent slope to 'one in x', x equals 100 divided by the percent slope.

To convert slope as 'one in x' to percent, divide 100 by x.

To convert slope in inches per chain to 'one in x', x equals 792 divided by the slope in inches per chain.

To convert slope as 'one in x' to inches per chain, divide 792 by x.

* For salinity conversions, note that a) there is no direct conversion between EM38 readings (mS/m) and soil extract EC values; values can be compared by calibrations, and b) the conversion between saturation extract values (EC_e) and 1:5 extract values ($EC_{1:5}$) depends on texture, and is given in Table 1. Many electrical conductivity meters have a scale that is labelled in mS rather than mS/cm, and µS rather than µS/cm.

Prefixes of SI units

Prefix	Meaning
deci, d	0.1 (one tenth)
centi, c	0.01 (one hundredth)
milli, m	0.001 (one thousandth)
micro, µ	0.000001 (one millionth)
nano, n	0.000000001
kilo, k	1000
mega, M	1,000,000

Queensland soil survey list

Northern Region — Region 1

- MDIA *Soils and Land Suitability of the Mareeba–Dimbulah Irrigation Area*, Enderlin, N
TAB *Soils and Land Suitability of the Atherton Tablelands North Queensland*. Malcolm D.
BBC *Wet Tropical Coast Study, North Queensland: Babinda/Cairns Area*. Smith, CD
CTI *Wet Tropical Coast Study, North Queensland: Cardwell/Tully/Innisfail Area*. Smith, CD

Herbert Region — Region 2

- WTC *Wet Tropical Coast, North Queensland: Ingham and Herbert River Section*. Wilson, PR

Burdekin Region — Region 3

- BER *Soil Survey: Elliot River to Bowen, Molongle Creek to Elliot River*. Aldrick, JM
BRB *Land Resources Survey of the Burdekin Right Bank, QLD*. Thompson, WP
BRL *Soils of the Lower Burdekin River Barratta Creek: Haughton River Area*. Reid, RE
BSA *Survey of the Soils of the Lower Burdekin Valley, North QLD*. Thompson, WP
HTC *Survey of the Burdekin River Irrigation Area: Haughton's Central Area*. Christianos, NG
HTN *Survey of the Burdekin River Irrigation Area: Haughton's Northern Area*.
Donnollan, TE
HTS *Survey of the Burdekin River Irrigation Area: Haughton's Southern Area*.
Donnollan, TE
IMC *Land Resources Survey of the Burdekin River Irrigation Area: Inkerman Central
Section*. Donnollan, TE
IMW *Land Resources Survey of the Burdekin River Irrigation Area: Inkerman West
Section*. Donnollan, TE
JFD *Soil Survey of the Burdekin Irrigation Area: Jarvisfield Section*. Day, KJ
LDR *Soil Survey of the Burdekin River Irrigation Area: Leichhardt Downs Relift*. Day, KJ
MLG *Burdekin River Irrigation Area: Mulgrave Section*. McClurg, JJ
MRE *Survey of the Millaroo Extension Area*. McClurg, JI
NHC *Land Resources Survey of the Burdekin River Irrigation Area: Northcote Section*.
McClurg, JI
NLH *Soil Survey of the Burdekin River Irrigation Area: Leichhardt Downs*. Donnollan, TE
RBO *Burdekin Right Bank Overview*. Donnollan, TE
SLK *Land Resources Survey of the Burdekin: Selkirk Area*. Loi, JK

Central Region- Proserpine to Mackay — Region 4

- MCL *Mackay Sugar Cane Land Suitability Study*. Holz, GK
PSS *Proserpine Integrated Land Use Study*. Hardy, S
PCS *Plane Creek Sugar-Cane Land Suitability Study*. Wills, AK

Southern Region: Bundaberg — Region 5

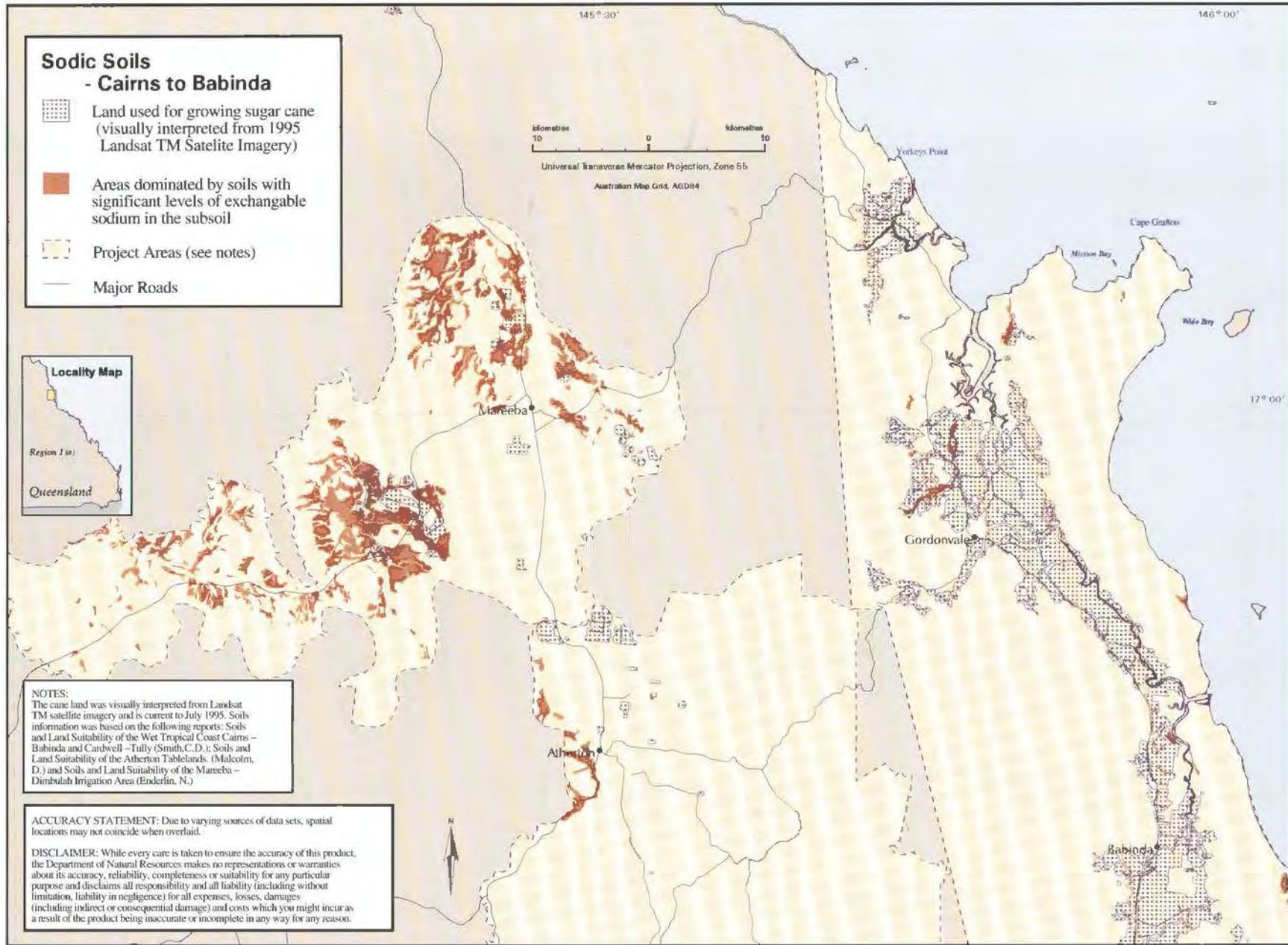
- CBW *Soils and Agricultural Suitability Assessment of the Coastal Burnett–Wide Bay
Region: Childer's Area*. Wilson, PR
BAB *Developing Sustainable Natural Resource Management Systems for Bundaberg*.
Donnollan, TE

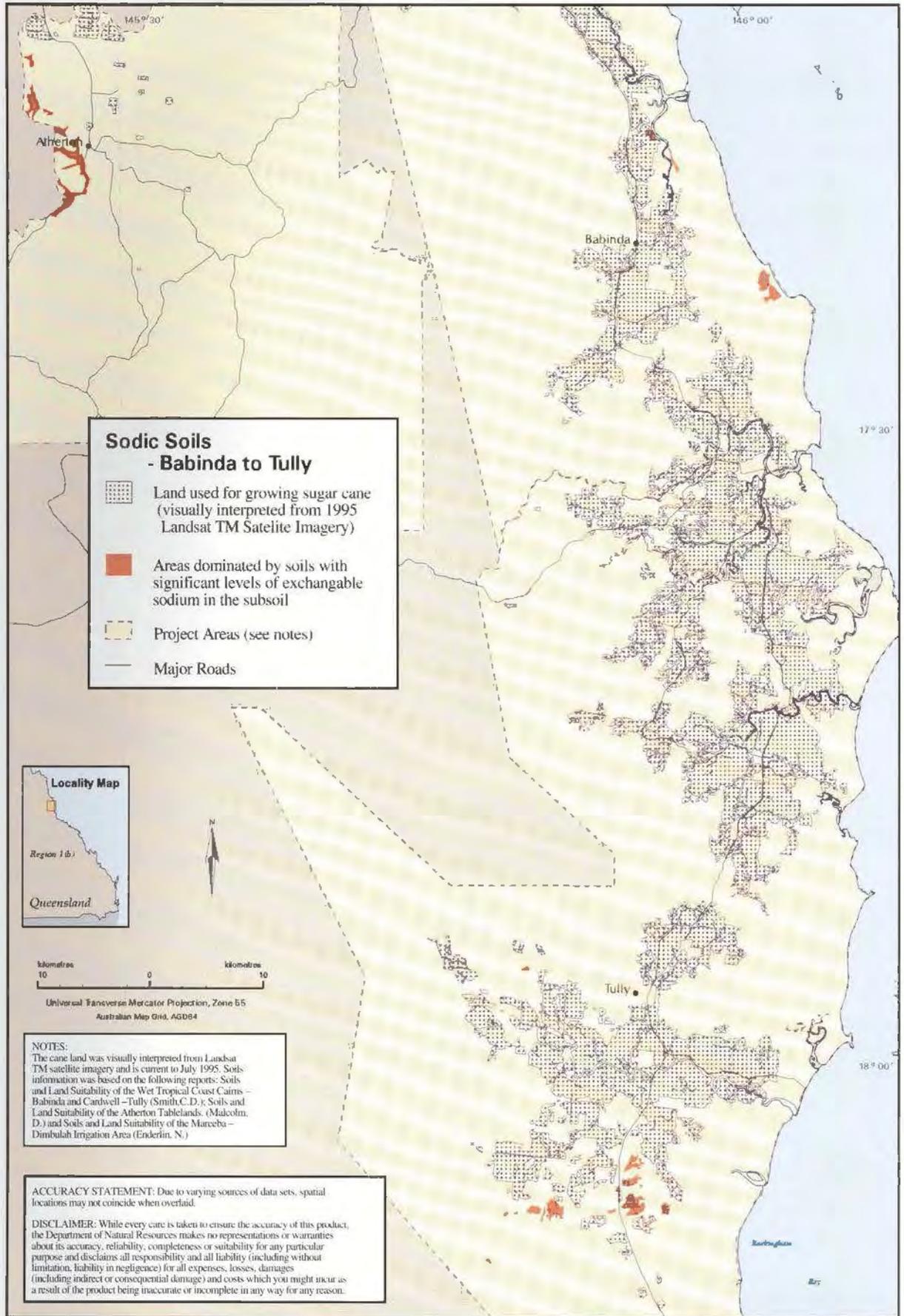
Southern Region: Maryborough — Region 6

- MHB *Developing Sustainable Natural Resource Management Systems for Maryborough*.
Wilson, PR

Provided by the Queensland Department of Natural Resources

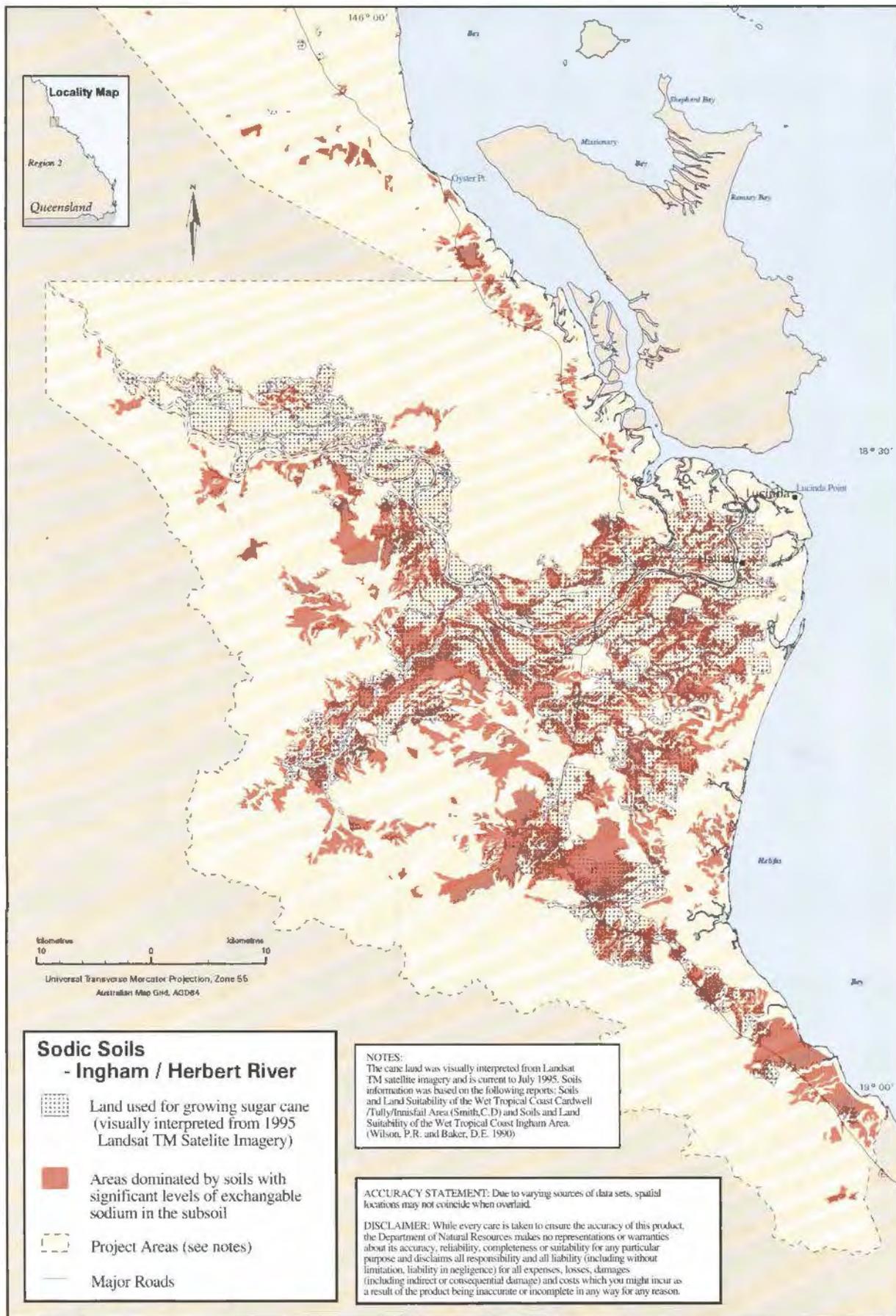
Maps of sodic soils in sugarcane districts of Queensland



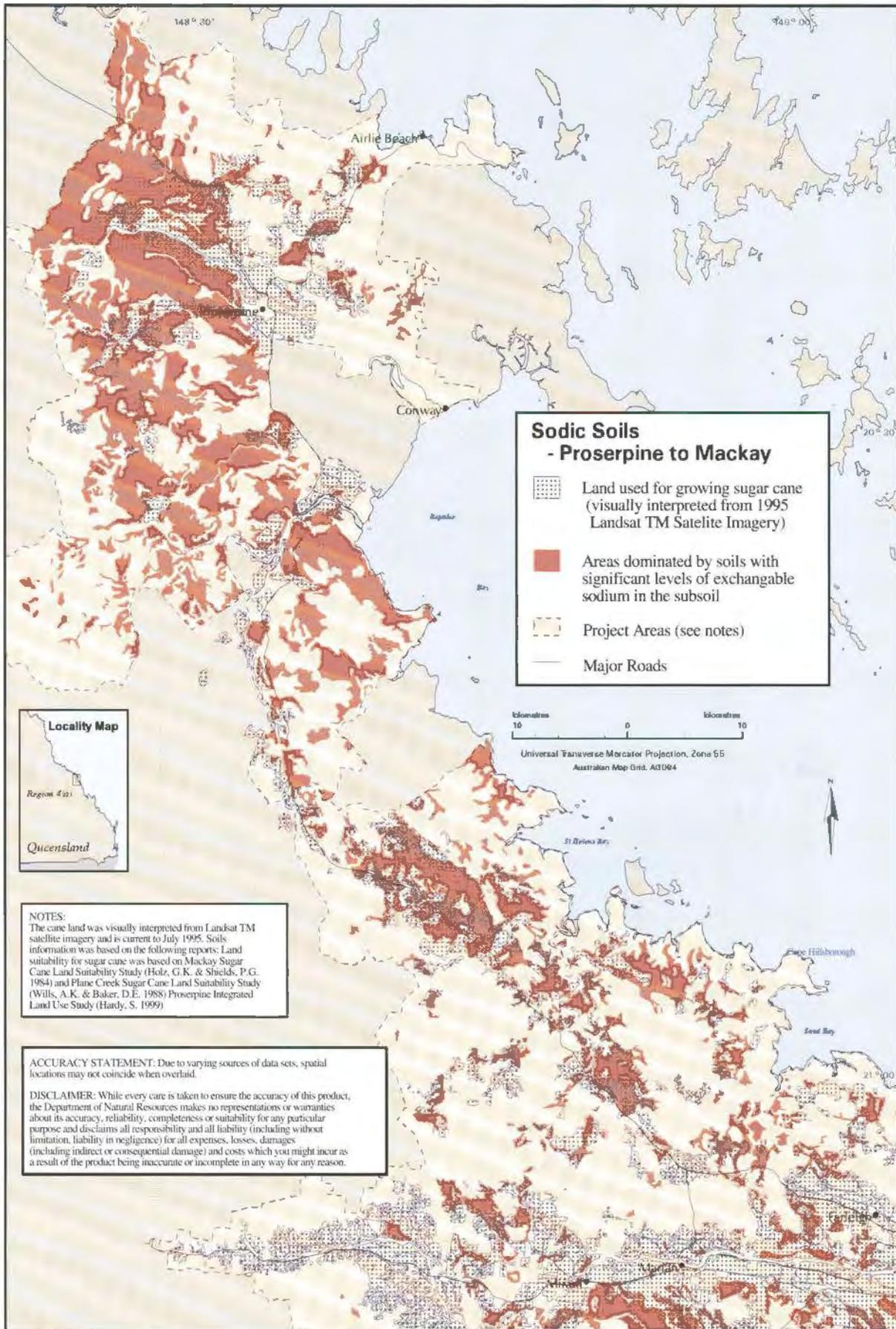


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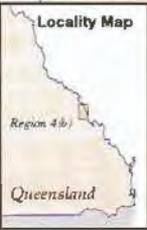
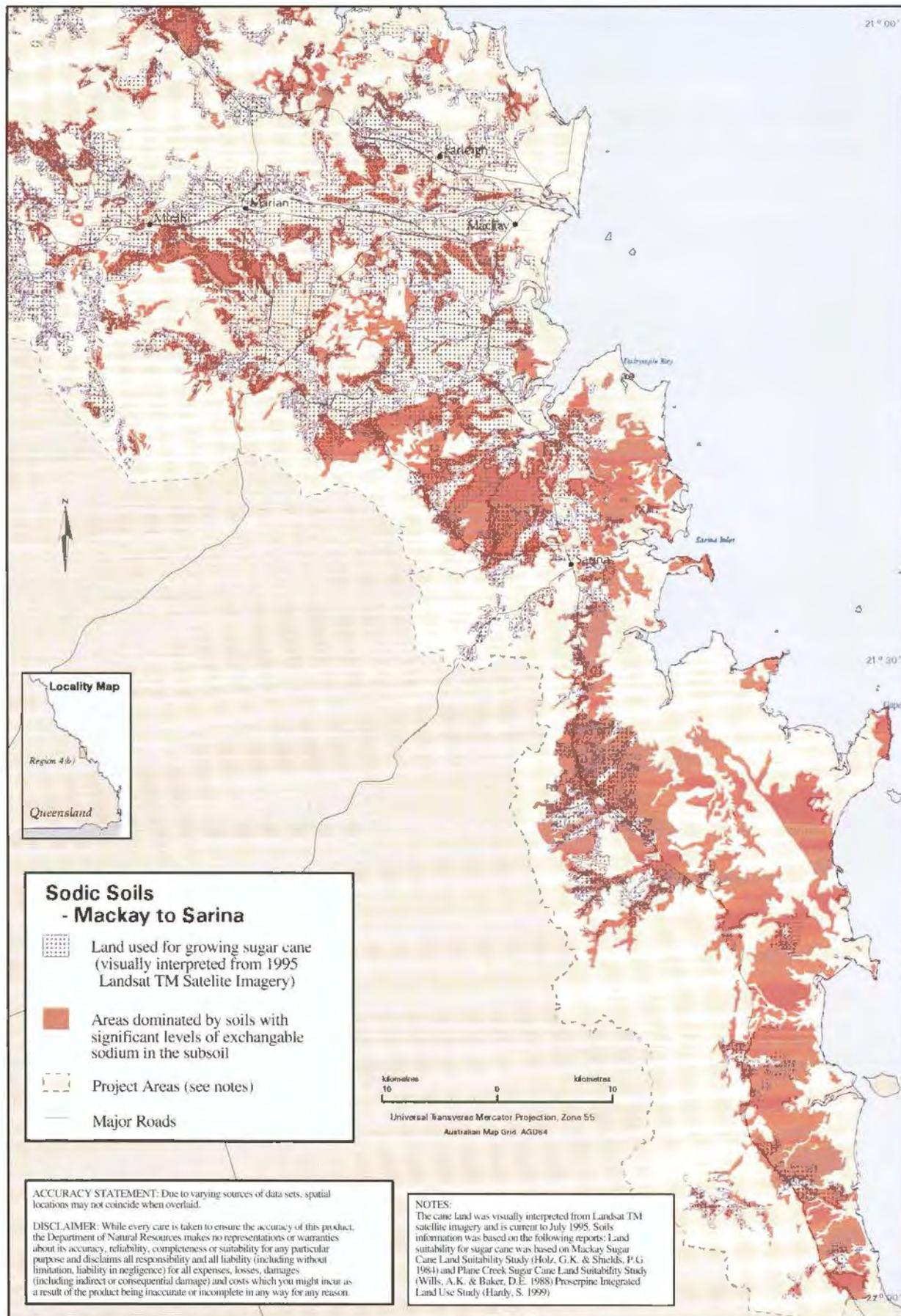






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**Sodic Soils
- Mackay to Sarina**

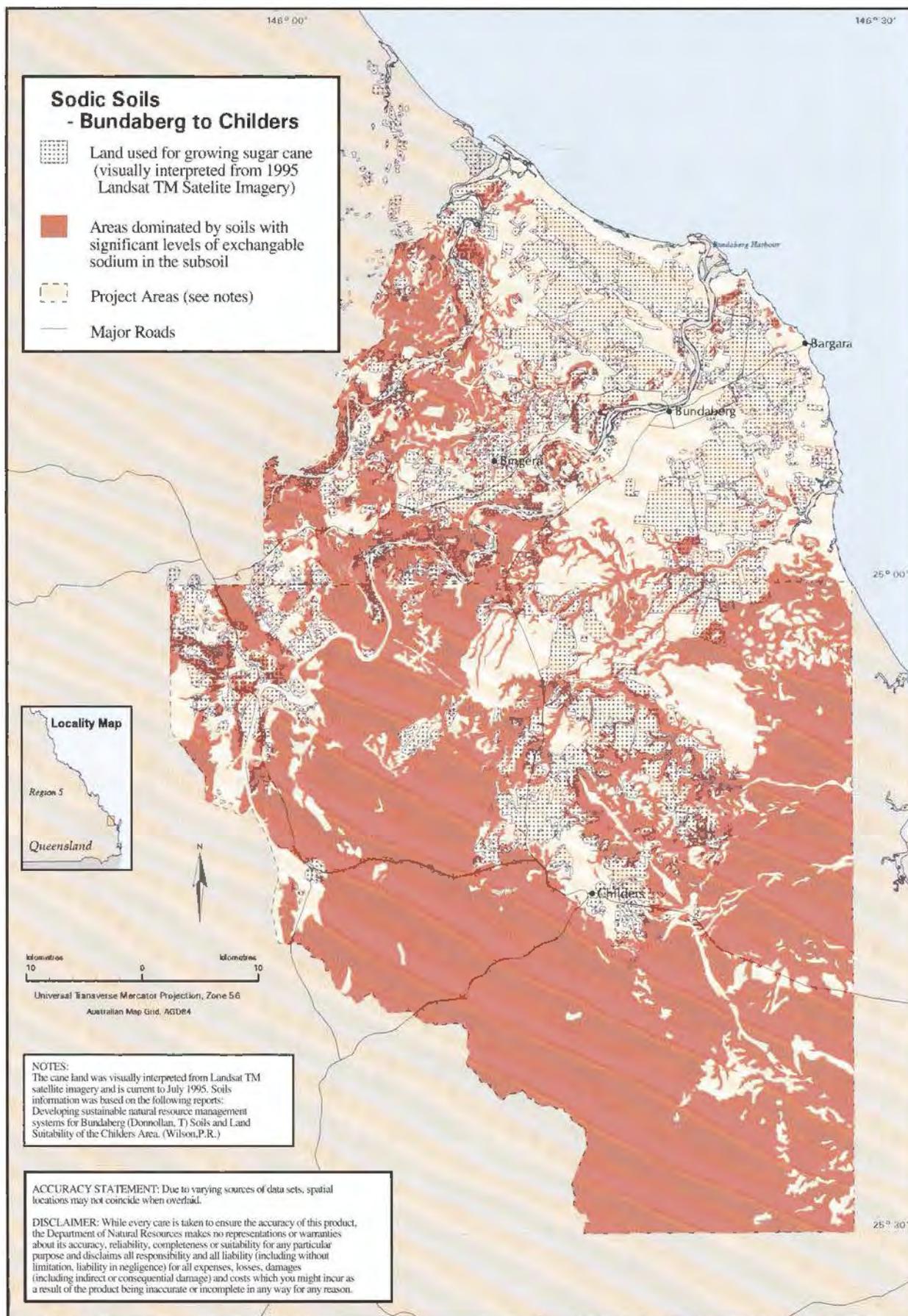
-  Land used for growing sugar cane (visually interpreted from 1995 Landsat TM Satellite Imagery)
-  Areas dominated by soils with significant levels of exchangeable sodium in the subsoil
-  Project Areas (see notes)
-  Major Roads

Kilometres 10 0 10
 Universal Transverse Mercator Projection, Zone 55
 Australian Map Grid - AGDS84

ACCURACY STATEMENT: Due to varying sources of data sets, spatial locations may not coincide when overlaid.

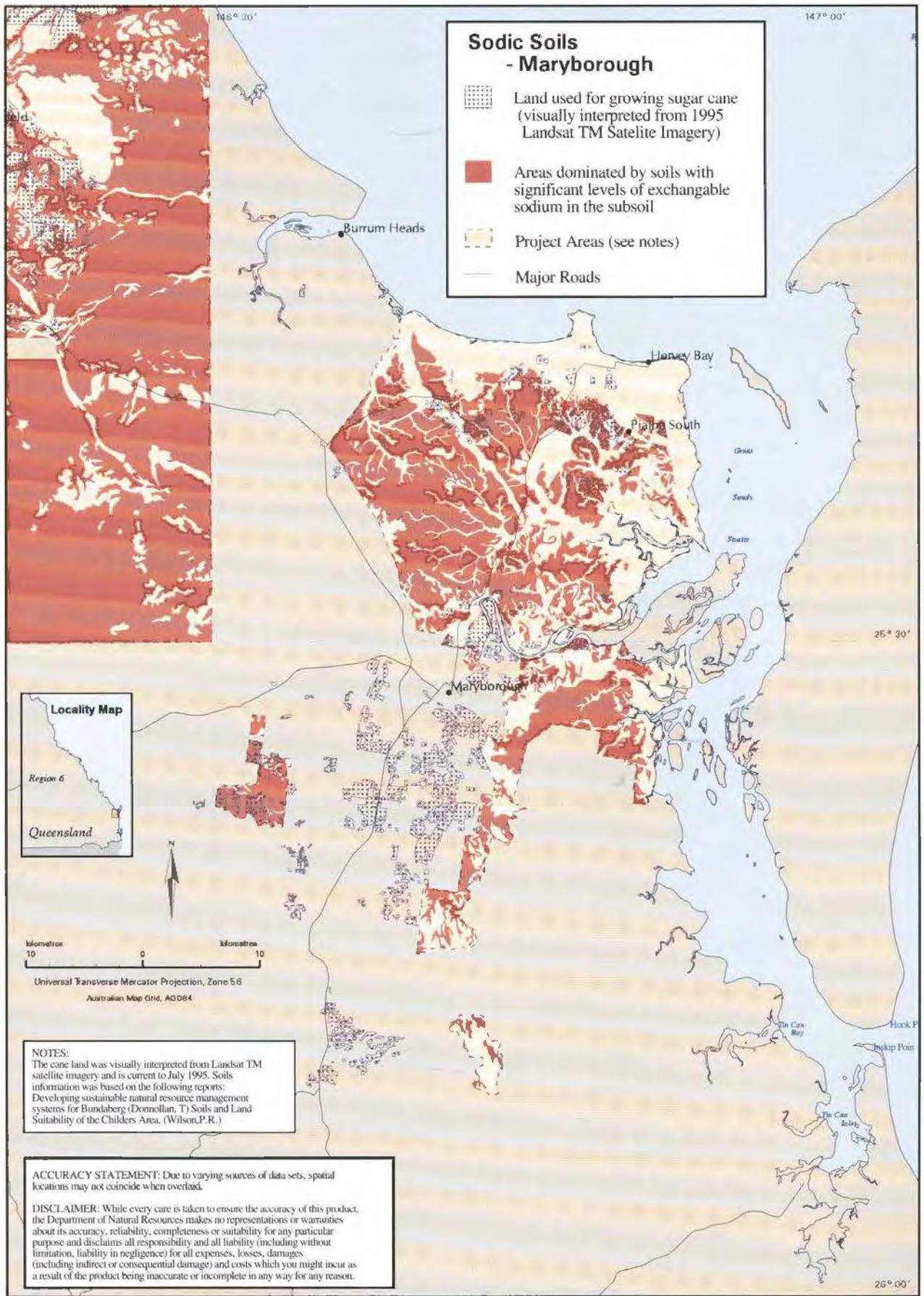
DISCLAIMER: While every care is taken to ensure the accuracy of this product, the Department of Natural Resources makes no representations or warranties about its accuracy, reliability, completeness or suitability for any particular purpose and disclaims all responsibility and all liability (including without limitation, liability in negligence) for all expenses, losses, damages (including indirect or consequential damage) and costs which you might incur as a result of the product being inaccurate or incomplete in any way for any reason.

NOTES:
 The cane land was visually interpreted from Landsat TM satellite imagery and is current to July 1995. Soils information was based on the following reports: Land suitability for sugar cane was based on Mackay Sugar Cane Land Suitability Study (Holz, G.K. & Shields, P.G. 1984) and Plane Creek Sugar Cane Land Suitability Study (Wills, A.K. & Baker, D.E. 1988) Proserpine Integrated Land Use Study (Hardy, S. 1999)



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BUILDING A DISSOLVENATOR

Several different types of dissolvenator are in use, manufactured by various companies. They may be fixed at a site or portable. A typical fixed type, based on the design of Peter Toomey, Burdekin cane grower, is described below.

Description

Gypsum, from the concrete GYPSUM BAY, is washed into the PRIMARY MIXER by using a jet of water. Between 12 and 29% of the water from the pump delivery is mixed with the gypsum in the primary mixer.

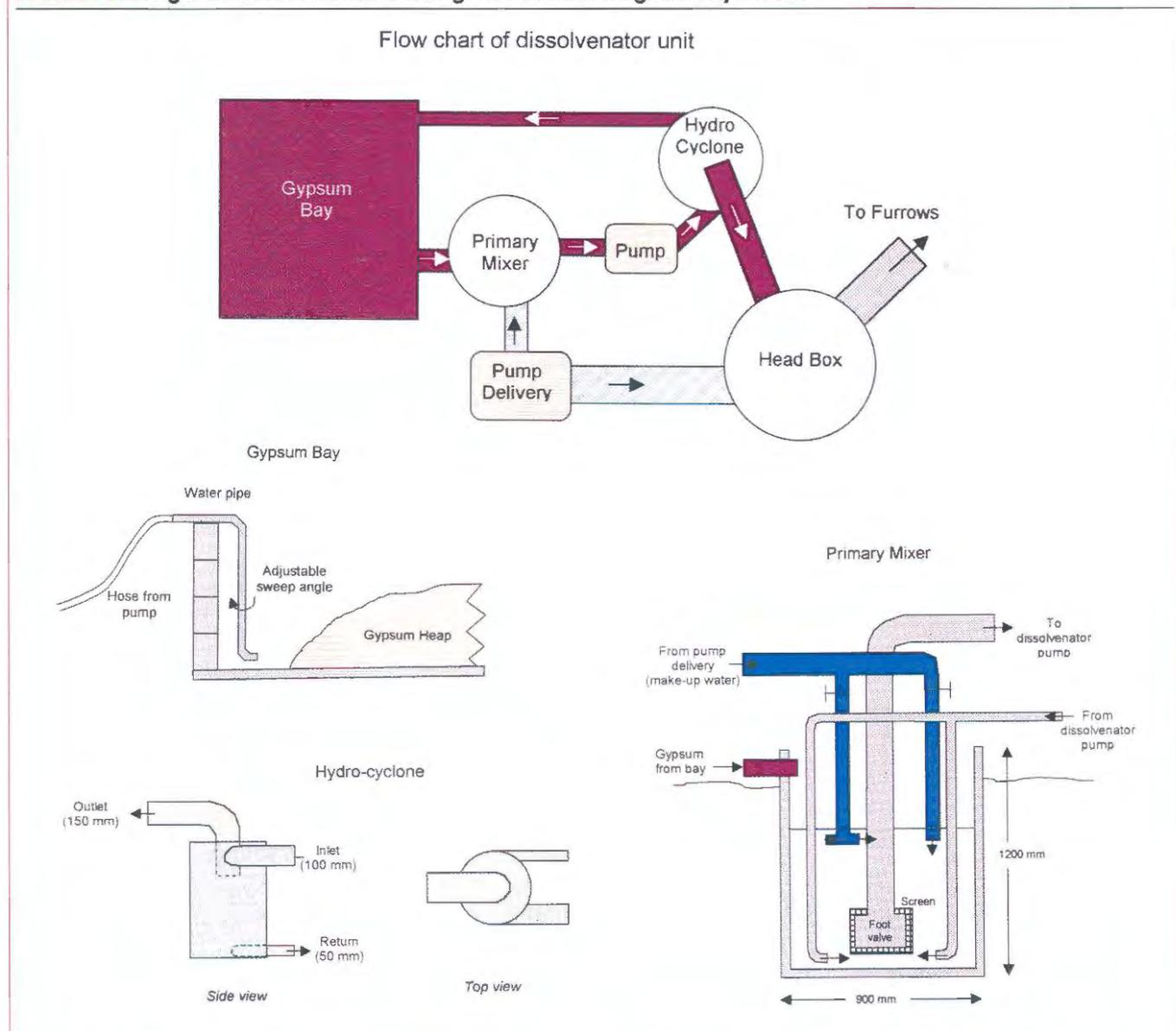
Water containing dissolved gypsum plus undissolved gypsum is pumped from the primary mixer to a HYDROCYCLONE, where the undissolved gypsum is separated and returned to the gypsum bay. The dissolved gypsum is discharged into the

head box where it mixes with the delivery water.

Gypsum bay

Concrete floor, sloped (10 mm/m) to corner nearest primary mixer. Concrete block walls on three sides, open on one side. Dimensions 4.4 m long x 3.2 m wide x 0.8 m high. A 100 mm diameter PVC pipe delivers gypsum from the lowest corner of the bay to the primary mixer. A 19 mm hose from the dissolvenator pump supplies water for washing gypsum from the heap. The hose is connected to a pipe fitted with a tap and nozzle. The pipe should be adjustable so that the sweep angle covered by the water jet covers the entire gypsum bay. The water jet should be directed at the base of the gypsum heap. A tarpaulin prevents rainfall from washing gypsum into the mixer.

FIGURE 33: A generic dissolvenator design for furrow irrigation systems.



Primary mixer

The primary mixer consists of a 1200 mm length of 900 mm diameter concrete pipe set into the ground near the gypsum bay. Water enters the mixer from the pump delivery via two lines controlled by gate valves.

A 50 mm float valve attached to one line allows control of the water level within the mixer. Alternatively, a depth sensor and solenoid valve can control the level.

Agitation is provided by water taken from the dissolvenator pump. It is delivered through two 19 mm water pipes to the bottom of the mixer. These pipes deliver water in a horizontal jet so that it circulates in a clockwise direction. A venturi may be fitted to introduce air into the system so as to maximise agitation.

Pump

As byproduct gypsum often contains impurities such as small stones, an open impeller type centrifugal pump is preferable. For closed impeller pumps a screen must be fitted before the inlet. If the pump is not self-priming a foot valve may be fitted.

Pump capacity will depend on the output of the irrigation pump and the total salt content of the water. The lower the EC of the water, the higher the proportion that must be passed through the dissolvenator in order to reach a given EC.

Calculation of the proportion of the irrigation that passes through the dissolvenator is discussed in the *Irrigation* section. The proportion of water passing through the dissolvenator may be varied automatically using an EC probe and solenoid valves.

Hydrocyclone

The hydrocyclone should be the same dimensions as a 200 L drum, ie 900 mm high and 600 mm diameter. Smaller hydrocyclones are less effective in separating the undissolved gypsum. Gypsum is quite corrosive, so it is advisable to paint the inside of the hydrocyclone.

The outlet should be set 150–200 mm into the drum. Placing the outlet below the inlet prevents the escape of undissolved gypsum. The inlet and return should be tangential to the drum as shown in the diagram. This maximises separation of the undissolved gypsum. A gate valve should be fitted to the return line. ▲

FIGURE 34: A dissolvenator unit in the Burdekin.





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