Dryland soil salinity - cure, containment or catastrophe?

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Abstract

This review considers salinity as a constraint to conventional agriculture with emphasis on recent developments in salinity research. We discuss the causes of soil salinization, and hydrological and agronomic strategies for improving production. Special attention is focused on (a) the importance of salinity and waterlogging as hazards to plant growth, and (b) the potential of halophytes as forage species.

Introduction

Dryland salinity is a major form of soil degradation in Western Australia. Over the last 150 years, about 300,000 ha of previously productive land have become too saline* for conventional agriculture (38). Given a continuing of current landuse practices a further 2.1 million ha of agricultural land could be affected over the next 10 to 200 years, with a large proportion of this developing within 30 years (38). Although these data imply a message of emerging environmental catastrophe, it should be stressed that there are important grounds for hope. In particular:

- We know the major causes of damage to plants on saline land (high salt concentrations and waterlogging).
- The hydrological changes in the soil which cause these stresses are understood.
- Management strategies are available which enable us to contain, and in some cases reduce, salinization and waterlogging.
- Valuable forage can be produced from saltland using salt and waterlogging tolerant halophyte shrubs.

This review considers each of the above areas; our aim has been to highlight some of the recent developments in salinity research in Western Australia. Given constraints of space, our treatment is brief; further details can be obtained by reference to the papers cited.

* Units of salinity. Soil salinities are conveniently measured as the electrical conductivity (in milliSiemens per meter) of the soil saturation extract (EC_e) or the solution in the growth medium. For purposes of conversion, a solution of NaC1 with an EC of 1000 mS/m contains about 100 mM NaC1 or 3550 mg/L chloride.

Salt and waterlogging - dual hazards for plants

It is now increasingly recognized that saltland is subject to two stresses which interact to affect plant growth and survival; these are (a) the accumulation of high salt concentrations in the soil, and (b) the occurrence of waterlogging.

For the last 50 years, studies have focused mainly on the effects of salt on plant growth and ion relations. These have shown that plant species differ substantially in their resistance to salinity; consequently classifications of the relative salt resistances of a wide range of plant genotypes are now available (17). Furthermore, it has become clear that most agriculturally significant species withstand low to moderate salinities by excluding salt at the root surface (17). Unfortunately correlations between salt concentrations in the external medium and plant growth (e.g. 21) are frequently of only limited use in predicting the yield of crops in the field. One explanation for this is that, in making these correlations, waterlogging has not been considered.

Waterlogging affects plants because it causes a 10,000-fold decrease in the diffusion of gases and volatile compounds into and out of the soil; thus 0_2 rapidly becomes deficient, and there is an accumulation of CO_2, ethylene and products of microbial respiration. These conditions have a variety of effects on plant growth and metabolism (reviewed in 10, 20, 29); most importantly, on saline soils there are increases in salt uptake and in salt concentrations in the shoots (reviewed in 4). For example, with wheat growing in sand cultures irrigated with a solution containing 60 mM NaC1, waterlogging caused 180% and 100% increases respectively in the rates of Na^+ and Cl^- uptake (root dry weight basis), and after 7 days of treatment, concentrations of Na^+ and Cl^- in the shoots of waterlogged plants were 100% and 50% higher respectively than in plants grown in drained sand (4).

The increased salt concentrations in the shoots of waterlogged plants have adverse effects on plant growth and survival in the longer term. For example, with Eucalyptus kondininensis, E. spathulata and E. comitae-vallis grown in sand culture irrigated with solutions with an EC of 4,200 mS/m, 11 weeks of waterlogging killed 55-75% of the plants, whereas only 0-5% of the plants were killed in salinized non-waterlogged pots (30). The consequences of salt/waterlogging interactions for agricultural species are evident from a study with wheat grown in nutrient solutions at various salt concentrations between 0 and 1,200 mS/m (3). At all salt concentrations greater than 200 mS/m, 30 days of N_2 bubbling of the solutions (simulating waterlogging) caused sufficient damage to plants to prevent any subsequent plant growth; in contrast, with plants grown in aerated solutions (simulating a non-waterlogged soil) growth continued even at salt concentrations as high as 1,200 mS/m (3). Although plants were not grown to maturity, it would appear likely that little or no grain yield would have occurred with N_2 bubbled plants at EC values greater than 200 mS/m. In soil, under well drained conditions, wheat yields are generally unaffected by electrical conductivities in the saturation extract (EC_e) of up to 600 mS/m and only reach zero at about 1,900 mS/m (21). Thus waterlogging appears to decrease the salt concentrations survived by wheat by a factor of 8.

Causes of soil salinization

The causes of soil salinization in Australia have received extensive treatment elsewhere (see reviews 22, 38, 39). Two factors are required for land to become salinized, a source of salt stored in the soil, and a hydrological disturbance which mobilizes the stored salts, transporting them to the soil surface.

Salt Accumulation

Most of the salt stored in Western Australia's ancient soil profiles has originated as air bourne saline dust which blows inland from the sea and falls in the rain. The dynamics of this accumulation can be illustrated from data collected on soils of the Belka Valley in the Merredin area

(7). In this area, the soil profiles are up to 50 m deep; laboratory analysis of drill cores shows that the soils of the valley contain an average of 650 t NaCl/ha (18). Since the rainfall here contains about 5.8 mg NaCl/L (22, 39), and the annual rainfall is about 340 mm per annum, a simple calculation shows that only about 33,000 years is required to account for the salt stored. This is a comparatively short period in an area in which soil formation has been occurring for millions of years.

Hydrology of Salinization

The major cause of soil salinization is the removal of native vegetation and its replacement by annual crops and pastures. More specifically we have replaced an ecosystem which transpires nearly all the incident rainfall, with an agricultural ecosystem which allows about 20 to 50 mm of rain a year to move into the deeper aquifers as drainage (13, 33). This causes an increase in water-tables, the mobilization of stored salt in the soil, and, where water-tables rise to within 1-2 m of the soil surface, the accumulation of salt at the soil surface.

Hydrologists recognize five hydrologically induced forms of salinity in Western Australia: (a) valley floor salinity in which there is groundwater discharge under pressure from deep semi-confined regional aquifer systems, (b) seeps caused by intrusive dykes, (c) seeps at the base of sandy rises, (d) seeps caused by bedrock highs, and (e) seeps caused by a change of slope. These forms and the factors responsible for salinization are shown schematically in Fig. 1. It is important to stress that in each of these situations overland flow, shallow subsoil seepage and high water-tables could cause waterlogging.

Hydrological management to improve production from salt affected soils

The development of hydrological strategies to improve production from salt affected soils has generated a large literature (recent reviews of symposia include 5, 19, 22 and 38). In most instances we would expect effective hydrological control to require combinations of both on-site and off-site strategies.

Off-site management

The aim of off-site management is to prevent water (surface water, shallow seepage, and recharge to the groundwater) moving to the saline area. Movement of surface water and shallow seepage can be deduced from observations of the terrain, and the textures of the surface and shallow subsoils. Methods for diverting surface and shallow sub-surface flows of water using banks, drains and interceptors are well established (see 8, 9 and 28). However, identification of areas of groundwater recharge and the reduction of this recharge presents special problems, which will be considered below.

Identification of recharge areas. Hydrologists recognize a variety of methods for detecting and quantifying areas of recharge and amounts of recharge (see 31); unfortunately these methods tend to be labour intensive and are not suited to the rapid assessment of large areas. However, one new technique which may have considerable potential in the identification of areas of recharge is that of electromagnetic induction. Where recharge is due to matrix flow through the bulk of the soil, salt appears to be displaced from the upper 10-15 m to greater depths in the soil profile; these soils therefore have low apparent electrical conductivity (ECa) values in the upper 10-15 m of the soil profile when measured by electromagnetic induction.

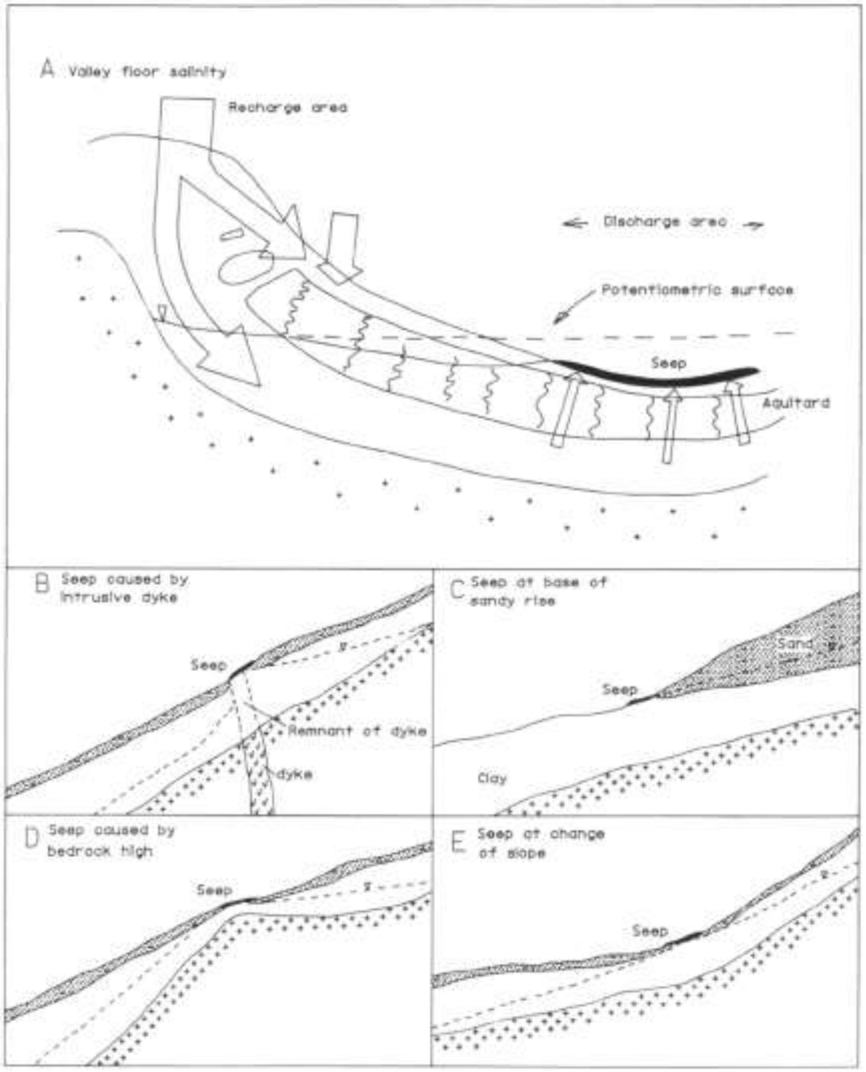

Fig. 1. Schematic representations of five methods of secondary soil salinization in Western Australia. A. Valley floor salinity; B. Seep caused by intrusive dyke; C. Seep at base of sandy rise; D. Seep caused by bedrock high; E. Seep caused by change of slope. In A, there are two aquifers, an unconfined surface aquifer (which contributes little salt but considerable water to the seepage area) and a semi-confined aquifer under pressure (which delivers small volumes of highly saline water into the upper soil layers through old root channels and cracks in the aquitard) (18). In B, C and D, seeps occur when water moves from situations of high to low hydraulic conductivity; in B and D groundwater moving downslope is impounded behind bedrock and a dyke respectively. In E, seeps occur because there is a reduction in hydraulic gradient downslope; the soils here cannot transport all the water being fed from upslope, and water builds up at the break of slope.

The potential of electromagnetic induction in the identification of recharge areas on a broad scale becomes apparent when it is realized that this kind of equipment can be installed in aircraft and used for airbourne surveys. However, despite this promise there needs to be a note of caution; not all recharge areas would be identified. In particular, in lateritic profiles in high rainfall areas there may be considerable recharge through preferred pathways (often old root channels). In these soils there would be transport of salt adjacent to the preferred pathway into the deeper subsoil, but there could still be quite high NaC1 levels in the bulk of the soil in the upper 10-15 m.*

Reduction of recharge. Since salinization is caused by an increase in water infiltration in recharge areas, it has been argued (31) that agronomic strategies which increase water use on recharge areas will also decrease (and in some cases reverse) rates of salinization. In support of this it should be noted that:

- The rates of recharge which give rise to salinity in Western Australia may be quite low; for example, in south-western Australia, where eucalypt forest and woodland has been replaced with a cereal-ley farming system, it is estimated that the additional recharge is only 20-50 mm per annum (13, 33), equivalent to 5-10% of annual rainfall.
- The substitution of deeper rooted crop species for shallow rooted annual pastures does decrease recharge. For example, at two sites in the Western Australian wheatbelt (Cunderdin and Kondut), Nulsen and Baxter (32) found that recharge beneath wheat, barley and lupin crops was substantially less than that under the more shallow rooted clover pastures; calculations from these data suggested that recharge beneath barley/lupin rotations would be only about 50% of that beneath wheat/clover/clover rotations (32).

To test the value of different recharge management strategies, the Western Australian Department of Agriculture has established trials on several wheatbelt catchments; regretably however, no catchment under study in Western Australia has yet been reclaimed by the growth of agricultural species on recharge areas. It therefore seems possible that salinization which has taken 20-50 years to occur may take a similar time to be reversed.

* For an example of a small catchment in which both kinds of recharge occur see Enge1 et al. (12). On catchment midslopes there were rapid rises in groundwater levels (consistent with recharge through preferred pathways) in soils that had high EC_a values in the upper 10-15 m; in contrast, higher in the catchment there were substantially slower rises in groundwater levels (consistent with recharge by matrix flow) in soils which had low EC_a values in the upper 10-15 m.

On-site Management

The aim of on-site management is to reduce waterlogging and salinity on the directly affected area. Three ways in which this has been done include: (a) the drainage of surface and subsurface water, (b) the ridging or forming of land so that some of it becomes less adversely affected, and (c) the mulching of soil to reduce capillary rise of salt to the soil surface. These strategies have been shown to be effective in ameliorating salinity and/or waterlogging (see 14 for benefits of subsurface drainage, 26 for improved establishment of saltbush due to ridging, and 37 for beneficial effects of mulch); however, these three strategies can be expensive. Cheaper amelioration of saline sites may be achieved using biological on-site treatments. In particular, George and colleagues (15, 16) have advocated the option of "discharge enhancement" using trees as biological pumps. In support of this, we are aware of at least two examples in which the growth of trees on or adjacent to a hillside seep and a sandplain seep have lowered local water-tables and "reclaimed" saline discharge areas (11 and R.J. George, pers. comm). Obviously, the use of trees to enhance discharge requires the selection of tolerant species which grow well on saline/waterlogged land (15). Consequently there is considerable interest in screening trees for salt and waterlogging tolerance (30). Unfortunately, the major problem with trees as a means of enhancing discharge is that they have little economic value in farming systems; however, it may be possible to profitably enhance discharge using halophyte shrubs (see below).

Saltland agronomy - profitable forage production from wasteland

One of the most exciting lines of research in Western Australia has been the development of salt tolerant (halophyte) shrubs as a means of obtaining forage production from saltland (see review 35). These species from the genera Atriplex and Maireana will withstand salt concentrations in root medium in excess of those found in sea water (c.f. 2 and review 17); in addition, at least some of these species are highly resistant to waterlogging (1).

The profitability of saltland agronomy and the factors affecting profitability have been analysed using linear programming techniques. Using the Western Australian Department of Agriculture's bio-economic mode1 MIDAS, Salerian et al. (36) have shown that for a given farm with salinity, profitability depends on:

(a) the cost of saltbush establishment, (b) levels of forage production, (c) the metabolizable energy concentration of the plants, and (d) commodity (wool and alternative sheep feed) prices.

With a typical farm of 1943 ha in the Maya shire with 210-280 ha of saline land, the mode1 suggests that revegetation with A. undulata would be profitable until establishment costs became as high as $90-110 per ha. (This calculation assumes a discount rate of 10%, and that A. undulata produces a forage yield of 0.86 t/ha equivalent to 17400 MJ/ha of metabolizable energy). The mode1 suggests that farm profitability is maximized by grazing saltland in late autumn to early winter and reducing the amount of grain fed to sheep.

In Western Australia most commercial revegetation of saltland presently occurs with only one saltbush species (A. undulata); saltbush plantations are established from seed using niche seeders similar to that developed by Malcolm and Allen (24), without fertilizer or deep ripping. However, there is substantial scope for improving production and profitability by (a) selecting more appropriate genotypes, (b) developing improved establishment techniques, and (c) developing appropriate fertilization strategies. More specific comments are made below.

Genotypes. Results of a number of experiments indicate that saltbush genotype plays an important role in pasture productivity. For example, with plants spaced at 3 m x 3 m intervals on a site with 0.3-0.4% Cl^- in the top 40 cm of the soil, the forage (leaves + twigs) production after 20 months growth was 64% and 36% higher with A. amnicola and A. paludosa respectively than with A. undulata (27). Furthermore, survival and recovery after grazing is strongly affected by genotype. In a long term trial in which pastures of A. amnicola, A. undulata and A. paludosa were grazed in late autumn for six successive years (25), the amounts of grazing obtained from the three species were initially very similar (1,700-2,000 sheep grazing days per hectare). However, by the end of the sixth year, the productivity of the A. undulata and A. paludosa pastures had fallen to 900-1,000 sheep grazing days per hectare, whereas the A. amnicola pasture produced 1,600 sheep grazing days per hectare. These changes coincided with the loss of 46% and 98% of the original A. undulata and A. paludosa plants respectively, but only 6% of the original A. amnicola plants (25).

Establishment. Natural regeneration of forage shrubs on salt affected soils is frequently slow. This may be for intrinsic reasons (reviewed in 23); for example (a) the percentage of seed fill in fruits and the percentage viability of those seeds may be quite low, and (b) the fruits of many Atriplex species contain water soluble germination inhibitors (NaC1 and saponin). In addition, there are a wide range of environmental conditions which adversely affect germination and establishment (e.g. salinity, waterlogging, drought, frost, low temperatures, weeds, insect attack, hail, soil slaking and crusting). We have recently initiated studies using alternative establishment methods to the niche seeder (nursery grown seedlings planted with tree or bare root seedling planters); preliminary results obtained using a tree planter with A. amnicola seedlings have been most promosing (6).

Nutrition. In any long term halophyte pasture, we would eventually expect productivity to decline as nutrients were removed offsite in grazed feed, fixed in unavailable forms in the soil, or leached below the root zone. Unfortunately, no information is yet available on the nutritional requirements of Atriplex species in the field, or on the benefits to production that can be achieved using fertilizers. However, pot experiments in the glasshouse suggest that there might be substantial improvements in growth using P fertilizers. In two separate experiments (34; Ratigen, Petersen and Barrett-Lennard, unpub.) in which A. amnicola was grown in a P-fixing agricultural soil, and A. bunburyana was grown in a mine dump soil, addition of P caused 3- and 6-fold increases respectively in shoot dry weight.

Concluding comments

Salinity in Western Australia is caused by hydrological changes due to the substitution of native vegetation by inappropriate crop and pasture systems. Given no change in present agricultural practises, salinization will continue with disastrous conseqeuences. Obviously, it is not feasible to cure salinity by returning the landscape to native vegetation; under these conditions agriculture would cease. However, it is possible to substantially modify our current agricultural practises to minimise the hydrological causes of salinization. In addition, we can obtain useful production from saline land using halophytes.

The reduction of salinity in Western Australia will require (a) an imaginative reappraisal and remodelling of current agricultural systems, and (b) the adoption of these systems by the farming community. Success is not assured; success requires the continuing of (a) financial support for research and development, and (b) active collaboration between researchers and farmers.

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