

Maximising Production of *Atriplex* Species

E.G. Barrett-Lennard*

Abstract

Results of a Western Australian bio-economic model (MIDAS) suggest that increasing the productivity of forage shrubs growing on salt-affected farmland can substantially increase whole farm profitability. Agronomic experimentation has shown that such improvements in productivity are achievable by deep ripping soils to reduce subsoil compaction, adding low levels of fertiliser, planting on less saline land and choosing more appropriate genotypes.

SALTLAND revegetation in Western Australia is currently conducted using simple seeding techniques with minimal inputs of fertiliser or deep tillage. While the species most commonly sown are *Atriplex undulata* and *A. lentiformis*, the preferred species is *A. amnicola* (Malcolm and Swaan 1989). Little documented information is available for Western Australia on the annual forage yields which can be achieved, but sustainable yields of 0.8–1.0 t/ha appear reasonable (cf. Malcolm et al. 1988; Malcolm and Pol 1986; Salerian et al. 1987). In contrast, in the USA and Israel, much higher yields (12–20 t/ha) were measured from stands of *Atriplex lentiformis* and *A. nummularia* when the plants were fertilised and irrigated (Watson et al. 1987; Aronson et al. 1988).

This paper examines the economic imperative for increasing the productivity of *Atriplex* stands in Western Australia, and shows that the productivity of such stands can be increased by planting on less saline land, deep ripping soils to reduce subsoil compaction and adding low levels of fertilizer, and choosing more appropriate genotypes.

Materials and Methods

Economic Modelling

The bio-economic model (MIDAS) of the Department

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of Agriculture was run to test the hypothesis that increased production of forage shrubs on salt-affected farmland could increase whole-farm profitability (cf. Barrett-Lennard et al. 1990). The subject of this model is a typical farm in the Esperance region of Western Australia, which has 1280 ha of non-saline land, and either 50 or 400 ha of saltland. It was assumed that 300 ha of the farm were cropped each year, that the stocking rate was 6–8 sheep/ha, that the farmer received \$6.00/kg for his wool and \$182/t for his feed grain, and that the annual amortised cost of saltbush establishment and maintenance was \$92/ha. It was also assumed that the forage had a digestibility of 55% (Malcolm et al. 1988), that all of the forage was available to be grazed, and that grazing had no effect on production in the following year.

Agronomic Studies

(a) Effects of salinity (Kamballup site)

Beds were formed on a clay soil on two adjacent sites (owned by G. Pieper and R. Bairstow). The beds were made with a road grader and were about 40 cm high and 5 m apart. Each site had four replicate beds about 100 m long. The beds were deep ripped to a depth of 40 cm, and fertilised with 72 g/m row of diammonium phosphate (DAP). Nurseryraised *A. amnicola* seedlings were planted 3 m apart on the beds in June 1990. Soil salinities (EC_e values) were measured in July 1990. Shoot canopy dimensions were measured after 15 months growth; canopy volumes were calculated from measurements of canopy diameter and height.

(b) *Effects of soil compaction and addition of fertilizer (Tammin site)*

This site had a sandy surface soil, with a traffic pan from 10 to 30 cm. The experiment had three ripping treatments: (a) a 'slot' rip treatment in which soil was disrupted to a depth of 40 cm in a band 40 cm wide; (b) an agroploUGH treatment in which soil was disrupted to a depth of 40 cm in a band 4.4 m wide; and (c) no rip. There were two fertilizer treatments: (a) 23 g/m row diammonium phosphate (DAP); and (b) no fertilizer. The experiment was planted on 27 September 1989. The experiment had four replicates; a replicate consisted of a row of 10 plants spaced 5 m apart. Shoot canopy dimensions were measured after 15 months growth; canopy volumes were calculated from measurements of canopy diameter and height. Forage production was estimated from the plant density (400 plants/ha) assuming that a plant of volume 1 m³ produces 1.1 kg of edible biomass (E.G. Barrett-Lennard, S. Hearn and K. Velterop, unpublished data).

(c) *Effects of genotype and plant density (Esperance site)*

Comparisons were made of the productivity of two *Atriplex* species at a range of planting densities at Esperance, Western Australia. The two species were *A. cinerea* (a vigorous prostrate shrub which forms adventitious roots when its procumbent branches touch the ground) and *A. amnicola* (an erect shrub which forms few adventitious roots). These were grown in blocks of 25 plants (in a 5 × 5 array) at densities of 2000, 1000, 500, 250 and 125 plants/ha. The experiment was planted on 7 September 1988. The growth (canopy dimensions and forage dry weight) of the central nine plants in each block was measured after 21 months.

Results and Discussion

Economic Modelling

Results of the model showed that saltland revegetation was highly profitable since the forage produced could be used to fill the feed gap which occurred in autumn and early winter.

Sensitivity analyses were done for three levels of forage production (1, 2 and 5 t/ha/year) for a farm with either 50 or 400 ha of saltland. With forage yields of only 1 t/ha, the value of revegetating an additional hectare of saltland with saltbush was \$28 (Table 1). The value of revegetating an additional hectare of saltland increased four-fold when forage production was increased to 2 t/ha, and increased five-fold to 18-fold when production was increased to 5 t/ha (Table 1). Interestingly, at the highest

Table 1. Effects of increases in productivity on the marginal value (\$/ha) of saltland revegetation for a typical farm in the Esperance area.

Area of saltland (ha)	Productivity (t/ha/year)		
	1	2	5
50	28	153	537
400	28	153	167

level of production, the value of revegetating saltland was higher when the area of saltland was 50 rather than 400 ha (Table 1). This was because once the autumn feed gap was filled, there was no further advantage to producing more forage from saltland.

Agronomic Studies

(a) *Effects of salinity*

Although little can be done to influence soil salinity in most dryland situations, it is important to know how salinity affects growth since it can assist in siting plantations at productive locations.

Studies of the growth rates of river saltbush (*A. amnicola*) in saline nutrient solutions (Aslam et al. 1986) have shown maximum growth occurs at 50 mol/m³, with a halving of growth at 400 mol/m³ NaCl. Evidence from the field also supports the contention that growth is affected by salinity.

Large differences in productivity of *A. amnicola* were obtained on clay soils at two adjacent sites at Kamballup, Western Australia. On the northern (Pieper) site, salinity levels in the upper 15 cm of the soil were 68% less, and plant productivity (determined from volume measurements) was 370% higher than on the southern (Bairstow) site (Fig. 1). The elevation of the beds, and the deep ripping and application of fertilizer all suggested that the differences in growth between these two sites were not due to waterlogging, soil compaction, or inadequate N or P.

(b) *Effects of soil compaction and addition of fertilizer*

After 15 months growth, plants grown without deep ripping or application of DAP had a volume of only 0.95 m³ (Table 2). The deep ripping and DAP treatments significantly ($P < 0.01$) increased shoot volumes. The 'slot' rip treatment disrupted about 10% of the traffic pan, and caused a 40% increase in average plant volume. In contrast, the agroploUGH disrupted about 90% of the traffic pan, and caused a 130% increase in average plant volume (Table 2). With each ripping treatment, DAP increased plant volumes by 13–58% (0.28–0.55 m³) (Table 2).

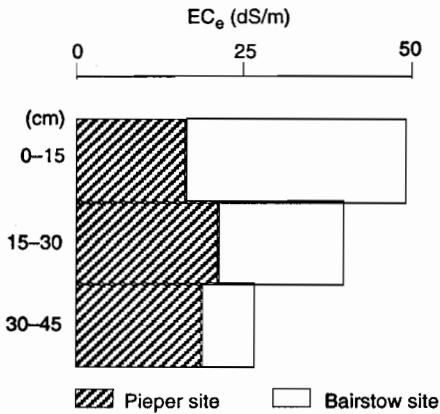


Fig. 1. Salinity profiles on clay soils at two adjacent sites (properties of R. Bairstow and G. Pieper) at Kamballup, Western Australia (E.G. Barrett-Lennard and K. Velterop, unpublished data). The volumes of the sites at 11 months were 1.43 m³ (Pieper site) and 0.30 m³ (Bairstow site).

Table 2. Effects of three ripping and two fertilizer treatments on the productivity of *A. amnicola* at Tammin, Western Australia (unpublished data of E.G. Barrett-Lennard and K. Velterop).

Treatment	Plant volume (m ³)	Estimated forage (t/ha)
No rip	0.95	0.42
No rip + DAP	1.50	0.66
'Slot' rip	1.35	0.59
'Slot' rip + DAP	1.83	0.81
Agroplough	2.18	0.96
Agroplough + DAP	2.46	1.08

(c) *Effects of genotype and plant spacing*

At close plant spacings (2.2 m × 2.2 m; 2000 plants/ha), *A. cinerea* produced 3.8 t/ha dry forage, which was 46% more than *A. amnicola* (Fig. 2). Measurements of shoot canopy diameters showed that *A. cinerea* plants were sufficiently wide-spreading to cover all the soil surface; in contrast, the canopies of *A. amnicola* covered only 47% of the soil (Fig. 3). At the widest plant spacings used in the trial (8.9 m × 8.9 m; 125 plants/ha), *A. cinerea* plants produced 1.68 t/ha dry forage, which was 180% more than *A. amnicola* at the same spacing, and similar to the productivity of *A. amnicola* at 1000 plants/ha (Fig. 2). At 125 plants/ha the percentage of soil covered by the shoot canopy was 49% for *A. cinerea*, but only 9% for *A. amnicola* (Fig. 3).

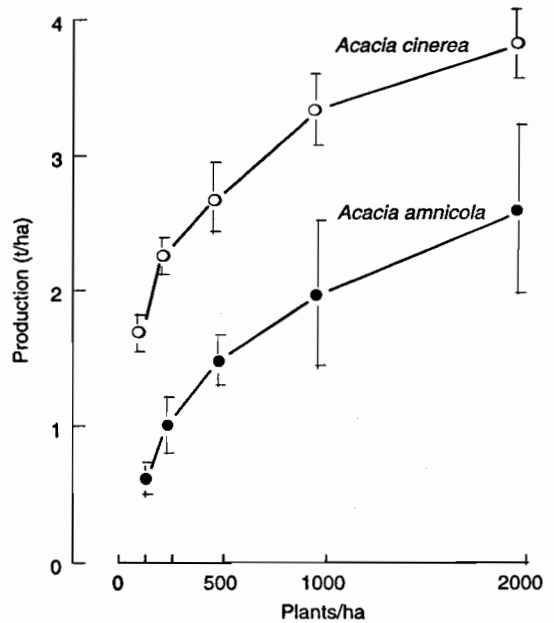


Fig. 2. Effects of plant spacing on forage production (t/ha dry matter) by *Acacia cinerea* and *A. amnicola* on a saline duplex soil at Esperance, Western Australia. Values are the means of four replicates, each replicate being the mean of 9 plants. Bars are standard errors (E.G. Barrett-Lennard and K. Velterop, unpublished data).

Discussion

The trials described here suggest that simple agronomic manipulations can improve the productivity of saltland, and that such improvements will increase farm profitability. In particular the results suggest the following.

1. *Costs of planting can be reduced by avoiding the most saline locations.*

These have far lower productivity than more moderately saline sites.

2. *On responsive soils, the benefits of deep ripping and fertilizer application outweigh the costs.*

At Tammin, the costs of establishing nursery-raised seedlings was about \$150/ha (\$120/ha for seedlings, \$30/ha for planting). The use of the agroplough and the application of fertilizer increased the total cost of revegetation by about 20% (\$30–40/ha), but these treatments increased forage production by 160% (Table 2).

3. *There can be considerable benefits to using improved genotypes.*

The results of the genotype comparison trial suggest two strategies for increasing the profitability of saltland revegetation.

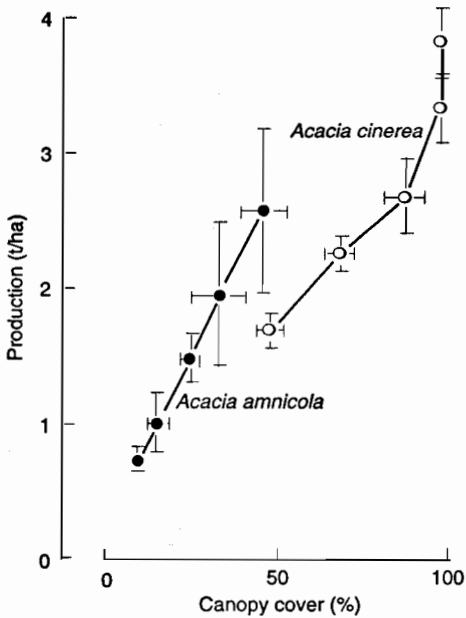


Fig. 3. Relationship between projected canopy cover (% soil surface covered) and forage production (t/ha dry matter) by two forage shrubs growing on a saline duplex soil at Esperance, Western Australia. Projected canopy cover was calculated from measurements of plant diameter. Values are means of four replicates as for Figure 2. Bars are standard errors (E.G. Barrett-Lennard, S. Hearn and K. Velterop, unpublished data).

(a) Reduce planting densities (and hence costs of establishment) without decreasing yields.

The data of Figure 2 suggest that the substitution of *Atriplex amnicola* at 1000 plants/ha by *A. cinerea* at 125 plants/ha would have no adverse effect on yield, but would reduce costs of establishment from about \$330/ha to \$70/ha (calculated assuming that nursery-raised seedlings cost \$0.30 each, and that land preparation costs \$30/ha).

(b) Maintain planting densities but increase yields.

The data of Figure 2 suggest that at 1000 plants/ha, the additional yields due to the substitution of *Atriplex amnicola* by *A. cinerea* would increase the value of saltland by about \$150/ha (interpolated from Table 1) (calculated assuming the costs of establishment used in Table 1).

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Effect of Plant Nutrition and Environment on the Seed Quality of *Atriplex amnicola*

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Abstract

The very low germination (27%) of *Atriplex amnicola* fruit collected from a salt-affected site at Tammin, Western Australia was attributed to low fruit fill. Fruit fill was high (80%) in early development stages but decreased dramatically to 35% at five months. Germination and fruit fill were similar indicating dormancy was not important.

Marked differences in fruit fill existed between the experimental sites but the individual measures of the environment (salinity, water relations, temperature and rainfall) and nutrition (nitrogen and phosphorus) investigated here appeared to be unrelated to fruit fill.

A variety of *Atriplex* species (e.g. *A. lentiformis*, *A. undulata* and *A. amnicola*) are being commercially seeded onto saltland in Western Australia. There is good evidence (Vlahos et al. 1991) that seed quality has contributed to failures in establishment. The percentage germination and fruit fill of the *Atriplex* species tested at the Western Australian Department of Agriculture are usually very low, less than 40%.

Environmental constraints such as nutrient deficiency, water availability and salinity have been shown to cause poor seed yield, but will not necessarily affect the germination percentage of plants (Austin 1972; Bolland et al. 1990; Thimmaiah et al. 1989). There has been little investigation of the effects of nutrition and environment on the seed quality of saltbush, other than work by Gerard (1978) who found no correlation between rainfall and fruit fill and seed germination in *A. canescens*.

Accordingly, the effects of nitrogen and phosphorus nutrition, soil salinity, temperature, rainfall and water stress on the fruit fill and germination of *Atriplex amnicola* were examined.

Methods

Two experiments, one on environmental factors, the other on nutritional factors affecting the seed quality of

Atriplex amnicola, were conducted on plots established at Tammin, 200 km east of Perth, Western Australia.

Environmental Constraints on Seed Quality

In salt-affected farmland, with duplex soils ranging greatly in texture, salinity and depth to the clay horizon, 12 plots of seedlings were established. Six plots of seedlings were established in a barley grass community, characteristic of mildly saline sites, and six in a samphire community, characteristic of more severely saline sites, and at a site where these communities interdigitate. Each quadrat consisted of a block of 36 *A. amnicola* plants (20 edge row and 16 experimental plants) planted at 5 m spacings. Female plants from the internal 16 plants were studied. All quadrats were planted by hand in August 1989 (Davidson, Galloway and Lazarescu, unpublished data).

The physical and chemical properties of the soil were examined. Measurements included EC_e (electrical conductivity of the saturated soil extract), pH, texture and description of the soil profile.

In midsummer (February 1991) pre-dawn leaf water potentials were measured along transects crossing two of the plots.

Nutritional Constraints on Seed Quality

On a relatively uniform mildly saline site, 28 plots (25 m × 25 m in area) were established. A randomised

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block design consisting of nitrogen treatments (0 and 60 kg/ha N, applied as AGRAN 34) and seven phosphorus treatments (0, 3, 6, 12, 24, 48, 96 kg/ha P, applied as superphosphate) with two replicates was adopted (Davidson, Galloway and Lazarescu, unpublished data). Trace elements and the above fertilizer treatments were rotivated into the top 10 cm of soil before planting.

Seedlings were planted in August 1989, at 5 m spacing, with 16 edge row and 9 experimental plants per plot. Female bushes from the internal 9 plants from the 0, 12 and 96 kg/ha P and 0 and 60 kg/ha N treatments were studied.

Seed Measurements

In both the above experiments plants began flowering in March–April 1990, fruits were collected monthly and assessed for fruit fill and fruit nitrogen and phosphorus content. Once seed was fully developed in November, ripened seeds were collected and final seed size, fruit fill and germination percentages were determined.

Results

Environmental Constraints on Seed Quality

During the first 5 months of fruit development (June–October), fruit fill was high (60–80%), although declining slightly. Fruit fill at the barley grass sites was significantly higher ($p < 0.05$) than at samphire sites (by about 10%) during this period. In November a dramatic drop to 35% fruit fill occurred for all plants, approximately half the original values, and site differences were lost (Fig. 1).

At this time (November) the fruit fill was higher than fruit germination by about 7%, indicating that a small proportion of embryos were dead or dormant.

A study of the environmental factors at the samphire and barley grass sites was unable to identify one major factor which might be influencing seed fill.

There was no correlation between soil salinity measurement made at the centre of the experimental plots and the fruit fill of the plants within the plot, although the relationship between salinity in the neighbourhood of each plant and its fruit fill was not tested.

There was no correlation between decline in seed fill and climatic extremes, despite there being a decrease in rainfall and an increase in temperature over the period in question.

Plants under water stress during February 1991 (mean leaf water potential = -4.5 MPa) did not differ in their final fruit fill or germination from plants at low stress (mean leaf water potential = -1.5 MPa). On the other hand, plants under less water stress at harvest had a greater proportion of large seeds.

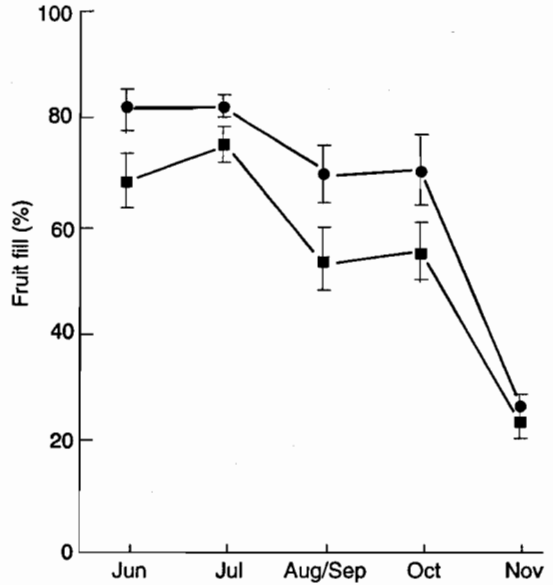


Fig. 1. Changes in fruit fill of *Atriplex amnicola* from flowering to harvest on highly saline (barley grass, ●) and mildly saline (samphire, ■) sites.

Nutritional Constraints on Seed Quality

Measurements made within the fertilizer plot indicated there was no effect of nitrogen and phosphorus fertilizers on fruit fill or seed germination. However, fruit fill at the fertilizer site (Fig. 2) was generally higher than both barley grass and samphire sites in the environmental study site (Fig. 1) and remained so throughout the ontogeny of the seeds.

Fruit fill was high (approximately 80%) for the first 5 months, although declining slightly with age (Fig. 2), in the same manner as the environmental study. In November, there was a sharp decline in fruit fill to 45% matching that which occurred in the environmental study plants (to 35%: Fig. 1).

Fruit phosphorus content remained constant throughout the experiment, while fruit nitrogen content declined from 2.5 to 1.3% (on a dry weight basis) in unison with, but at levels generally lower than, leaf nitrogen (Fig. 3).

Discussion

The individual measures of the environment (salinity, water relations, temperature and rainfall) and nutrition (nitrogen and phosphorus) studied at Tammin did not appear to affect fruit fill or seed germination of *Atriplex amnicola*. Despite this, fruit fill at the fertilizer trial dif-

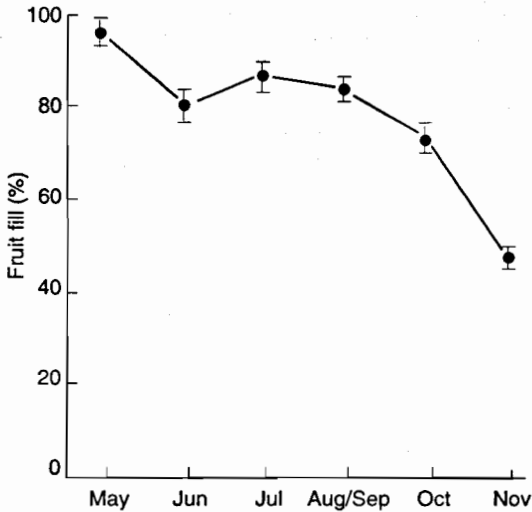


Fig. 2. Fruit fill of *Atriplex amnicola* from flowering to harvest — fertilizer trial.

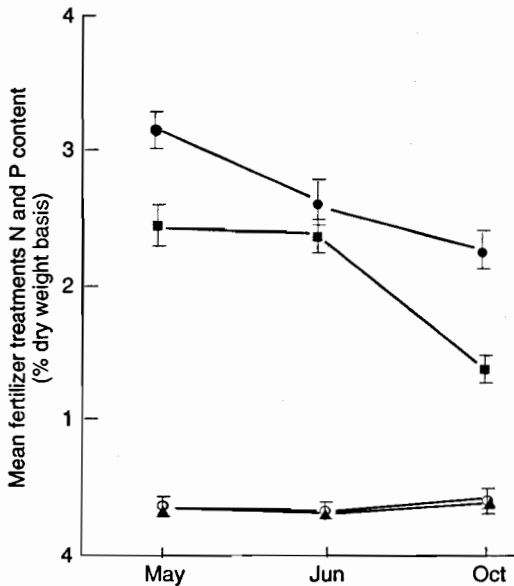


Fig. 3. Leaf and fruit nitrogen and phosphorus levels from flowering to harvest in fertilizer trial: ●, leaf N; ■, fruit N; ○, fruit P; ▲, leaf P.

ferred markedly from both the barley grass and the samphire sites of the environmental trial indicating that there was a strong local environmental effect on fruit fill.

There are numerous possible reasons for this apparent contradiction. The physical and chemical environments within each plot at Tammin have been shown to be very

heterogeneous with large variations in conditions over distances less than 5 m (Davidson, Galloway and Lazarescu, unpublished data). Therefore, studies of this type should be conducted on individual plants not on whole plots. The subset of variables tested in this experiment may not have included the critical factor influencing fruit fill. Alternatively, there may have been a complex of factors that interact to affect fruit fill.

Germination and fruit fill of *A. amnicola* were very similar indicating that seed dormancy was not important, but that seed abortion and fruit fill are not the same. Abortion is loss of fruit fill, the major factor in determining seed quality. Similar conclusions were drawn for *Atriplex canescens* (Gerard 1978).

The rapid decline in fruit fill (through seed abortion) from October to November 1990 is unexplained, although it coincided with a decrease in rainfall and a rise in temperature. Plants under low water stress have a greater proportion of large fruits but did not differ in fruit fill from plants under high water stress.

The nitrogen content of fruit was significantly lower than that of the leaves and decreased during the experiment. This agrees with studies of Austin (1972).

Fruit phosphorus contents did not change during the experiment.

This study agrees with previous research which shows the typical plant response to an adverse environment is a reduction in seed yield (in this case by reduction in seed fill) rather than in seed germination (quality refers to fill and germination) (Delouche 1980) although it would be necessary to assess total seed productions per bush in each environment to prove this for *A. amnicola*. This mechanism ensures survival of the species through few high quality seeds, rather than numerous poor quality seeds. Only extreme environmental variation during seed development will affect viability (Austin 1972).

Further research is required to identify the environmental or genetic factors causing a sudden drop in fruit fill between October and November.

Acknowledgments

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Nitrogen Concentrations for Optimal Growth of *Atriplex amnicola*

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Abstract

In a glasshouse study, conducted in sand culture flushed with excess modified Hoaglands solution, *Atriplex amnicola* cuttings responded strongly to application of ammonium nitrate at two salinities. The response to nitrogen was more pronounced at low salinity.

Maximum growth was obtained at a nitrogen concentration of 7.14 mM at low salinity (50 mM) and 14.28 mM at high salinity (400 mM).

Despite the strong responses to nitrogen fertiliser observed in the glasshouse, no response was obtained by applying nitrogen fertiliser in the field.

A wide range of studies has been conducted where nitrogen fertilizer was applied to halophytic shrubs, both in the field and the glasshouse (e.g. Chatterton et al. 1971; Drake and Ungar 1989). These studies have yielded an equally wide range of conclusions on the benefits.

For example, in a glasshouse study investigating combinations of nitrogen fertilizer and salinity, Chatterton et al. (1971) reported no significant increase in growth of *Atriplex polycarpa* at nitrogen concentrations greater than 2 mM. They concluded that, although the concentrations of nitrogen in soils were generally low, nitrogen was efficiently absorbed and non-limiting.

In contrast, Drake and Ungar (1989) found nitrogen supply to be the most important factor limiting the growth and reproduction of *Atriplex triangularis* in glasshouse experiments. No response was obtained by applying nitrogen in the field.

The aim of the current experiment was to determine the nitrogen concentration which produces the optimal growth in *Atriplex amnicola* (river saltbush) and to recommend rates of nitrogen fertilizer application in the field.

Materials and Methods

Cuttings of *A. amnicola* (971) were struck, then grown

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for 30 days in moist sand before even-sized individuals were transplanted into 25-cm diameter plastic pots filled with sand. Single cuttings were transplanted into each of the 9 replicate pots for the five levels of nitrogen and two levels of salinity in the experiment (ten treatments in all).

Nitrogen was applied as ammonium nitrate at rates of 1.79, 3.57, 7.14, 14.28 and 28.57 mM in saline 1/10 Hoaglands solution. The two salinities used were 50 and 400 mM NaCl, applied stepwise by 50 mM increments every second day.

The saline nutrient solutions were supplied in excess (500 mL) twice daily. The effluent was collected in reservoirs beneath the experimental benches and subsamples were collected daily for analysis of pH, nitrogen, potassium and electrical conductivity (EC).

Plant height, crown diameter, the growth rates of apical shoots and numbers of shoots were recorded weekly until a final harvest at 35 days. Harvested plants were divided into roots, stems and leaves and the fresh and dry weights obtained. Subsamples of each plant fraction were then analysed for N, K, Na and Cl.

Results

Growth of *A. amnicola* cuttings (plant volume: Fig. 1) responded strongly to application of ammonium nitrate. The nitrogen response curve was approximated by a cubic function ($R^2 = 0.96$ to 0.99) which indicated nitrogen concentrations of 10 and 11.5 mM for optimal

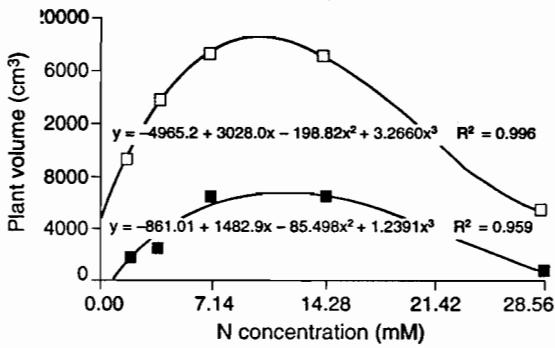


Fig. 1. The effect of five levels of nitrogen on plant volume of *Atriplex amnicola*.

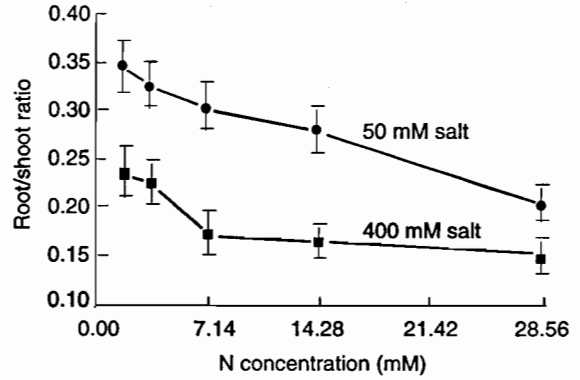


Fig. 2. The effect of five levels of nitrogen on the root/shoot ratio of *Atriplex amnicola*.

growth of *A. amnicola* at 50 and 400 mM NaCl (see Fig. 1). The response to nitrogen was much more pronounced at low salinity where rates of growth were 2 to 3 fold greater than at high salinity.

The ratio of root to shoot declined as the external concentration of nitrogen was increased in both salinity treatments (Fig. 2) but was more marked at low salinity. This indicated that there was a greater investment of resources in root development when nitrogen was limiting.

Discussion

In a glasshouse trial, conducted in sand culture, *A. amnicola* cuttings exhibited a very marked response to the rate of application of ammonium nitrate fertilizer. Optimum growth rates were obtained at nitrogen concentrations of approximately 10 mM.

In the USA and Israel, rates of productivity from stands of *Atriplex*, irrigated with saline water, can be high as 12 to 20 t/ha/year of dry matter (Aronson et al. 1988; Watson et al. 1987). Production from plots of *Atriplex* in Western Australia rarely exceeds 2 t/ha.

Field experiments, conducted in shallow duplex soils at Tammin in Western Australia, demonstrated that, although there was a marked initial response to nitrogen application (40% increase relative to controls, at 3 months) at rates up to 60 kg/ha, the nitrogen response declined to 10% after 2 years.

Despite the strong response of *A. amnicola* to nitrogen in the glasshouse, application of nitrogen fertilizer in the field can only be recommended to facilitate early establishment of *Atriplex* plantations. A number of severe environmental constraints, other than nutrition, are operating in salt-affected land in Western Australia (Davidson et al., these proceedings). Application of fertilizers will be highly beneficial only when other environmental conditions are non-limiting. These conclusions are supported by previous studies on nitrogen nutrition of chenopods.

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Factors Affecting Saltbush Establishment on Saline Soils in Southwest Australia

S. Vlahos*

Abstract

Many plant, soil and climatic factors affect the establishment of saltbush (*Atriplex* species) on saline soils. Germination levels of saltbush seed vary from 0 to 75% and are usually below 40%. Germination is reduced by high salinity and low temperatures which are interactive in their effect on germination. Seed burial, insect pests and weed competition also reduce establishment. Niche seeding was developed to reduce these limitations to saltbush establishment on saline soils.

It is estimated that 315 000 ha of cleared land is too saline for conventional crop/pasture production in the agricultural region of Western Australia. It is further predicted that up to 2.1 million ha of productive land in the next 30 years has the potential to become saline (Western Australian Department of Agriculture 1988).

Saline land has the potential to grow salt-tolerant shrubs (saltbushes) for sheep forage (Malcolm 1986, 1989; Runciman 1986). In order to achieve this an establishment technique is required to revegetate saltland. To be effective the technique must be both reliable and economically viable. Planting nursery raised seedlings is a very reliable, but the estimated costs for establishing saltbush by seedlings is \$500/ha. This is based on planting *Atriplex amnicola* (river saltbush) on a 3 × 3 m spacing (1100/ha) at a seedling and planting cost of \$0.45 each.

Establishing saltbush by direct seeding can be effective and is relatively cheap, but is an unreliable method. Contractors currently direct seed saltbush by the niche seeding technique for \$150–300/ha. A further \$20–60/ha needs to be added to cover costs for weed and insect control and cultivation. A farmer in the North Stirlings District has calculated an establishment cost \$155/ha over an area of 20 ha.

The Process of Establishment

Establishment of *Atriplex* from seed can be divided into the three phases of germination, emergence and early growth.

Germination involves the imbibing of the seed and emergence of the embryo from the seed coat. In the case of *Atriplex*, germination may involve the protrusion of the radicle/cotyledons from the fruit which surrounds the seed. In the second phase of establishment the seedling emerges from the soil surface. This is important as seeds may germinate but the seedling may be unable to penetrate the soil.

The final stage of establishment is early growth. During this phase the energy and materials required become less dependent on the seed reserves and derived from root uptake and photosynthesis.

There are many climatic, soil, and biotic factors which affect establishment (Table 1). Some of these can be limiting establishment at all stages, e.g. salinity.

This paper discusses some of the factors which limit the establishment of *Atriplex* from seed on saline soil in Western Australia and describe the technique of 'niche seeding' developed to improve the reliability of establishment.

Seed Quality

Saltbush seed is surrounded by two bracts which form a false fruit and may not contain a viable seed. The most

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Table 1. Factors affecting the establishment of *Atriplex*.

Climatic	Soil	Biota
Precipitation total seasonal pattern intensity reliability	Physical texture water retention crusting infiltration	weeds diseases insects grazing animals seed quality
Temperature maxima minima	slaking, dispersion stability when dry bulk, penetrability frost	
wind	Chemical pH salinity toxicity fertility	
	Landscape slope aspect	
	Hydrology runon runoff waterlogging	

important factor affecting the germination of *Atriplex* is the quality of the fruit sown. Seed quality includes the percent germination and purity of the seed lot. There are many cases of establishment failure which were directly attributed to poor quality seed.

The need for seed testing is due to the highly variable quality of the seed. Germination levels range from 0 to 80% depending on seed lot. For *A. amnicola*, 50% of seed lots tested by the Seed Testing Station at the Western Australian Department of Agriculture during 1989–90 had germination levels of less than 25%. For *A. undulata* one-third of the seed lots tested had germination rates of less than 5%.

The cause of the variable seed quality is unknown. Seed testing overcomes the problem of variable seed quality by ensuring enough viable seed is sown.

Salinity

Salinity is the most obvious soil factor affecting establishment on saline soil. The germination of *Atriplex* decreases with increasing salinity. For *A. amnicola* germination is reduced by 50% at 250 mM NaCl (approximately 24 dS/m). At 500 mM NaCl (44 dS/m), germination is almost totally prevented (Fig. 1).

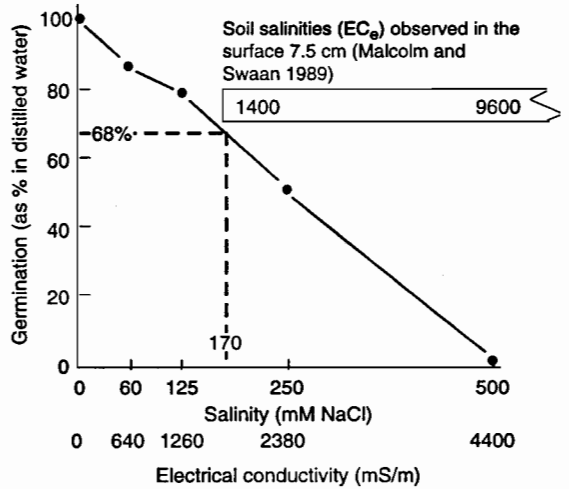


Fig. 1. The effect of NaCl concentration on the germination of *Atriplex amnicola*.

Salinity levels in the soil surface change with the seasons. It is highest at the end of summer when salts have accumulated in the soil surface due to capillary rise and lowest in winter when rains have flushed the salt down the soil profile. Thus germination may be possible during winter when the surface salinity is at its lowest.

A feature of *Atriplex* is that high salinity does not kill the ungerminated seed, it only inhibits germination. When ungerminated seeds of *A. amnicola* are kept in a solution of 500 mM NaCl for 52 days, and are placed in distilled water they germinated to the same level as those kept in fresh water.

This means seed can be sown into soil which may be too saline for germination and wait, for at least 7 weeks, for salinity conditions to ameliorate for germination.

Temperature

During the wetter months of winter (June–August) when surface salinities are reduced, temperatures are also much lower.

Atriplex germination is inhibited at low temperatures. The germination of *A. amnicola* after 8 days is only 10% under a temperature regime of 4–15°C. Raising the temperature to 8–15°C increased germination to 70%.

Low temperature and high salinity interact to depress germination even further. For *A. amnicola* germination is reduced by 30% at a salinity of 170 mM NaCl (Fig. 2). At a temperature regime of 8–15°C germination is reduced by 20%. Thus at a salinity of 170 mM and 8–15°C the expected germination is 55–60%. However, germination under these conditions is only 4% indicating the interaction of high salinity and low temperature on

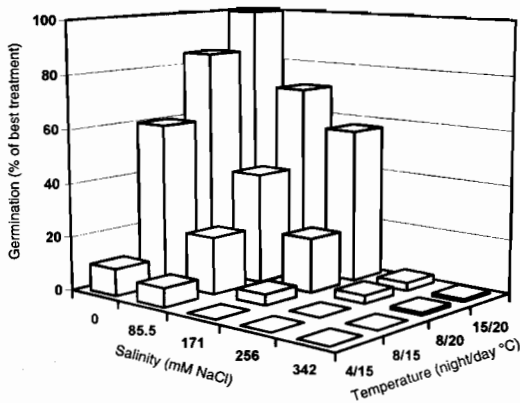


Fig. 2. The interactive effect of temperature and salinity on the germination of *Atriplex annicola* (data provided by C.V. Malcolm).

germination (Fig. 2). Thus, during winter, germination may be inhibited by both salinity and temperature, despite the relatively low salinity.

Factors Affecting Emergence

Once the seed has germinated the seedling must emerge through the soil. Wind, rain and dispersive and slaking soils have been found to reduce the emergence of *Atriplex*.

Seed Burial

A. annicola emergence is very sensitive to depth of burial. A covering of 2 mm reduced emergence by 50% and almost prevented emergence at 5 mm.

Factors Affecting Early Growth

Once the seedling has emerged it has a range of other conditions to contend with.

Insects

Insects including the red-legged earth mite and aphids have been observed to feed on the small seedlings. It is a standard recommendation that 2–3 weeks after sowing the area be treated with insecticide.

Weed Competition

The technique of niche seeding ameliorates the soil not only for the *Atriplex* but also for the weeds including

barley grass and rye grass. Often where there has been poor weed control rye grass will be absent or scarce on the soil between the mounds but growing vigorously in the niche mounds.

In a field trial determining the effect of the pre-emergent herbicide carmetamide, establishment was increased threefold and seedlings were four times as high in the treated plots. This was associated with a tenfold reduction in weed numbers and halving of the weed biomass.

Niche Seeding Techniques to Improve *Atriplex* Establishment

Niche seeding was developed to improve the establishment of shrubs on saline soil. As its name implies, it involves engineering a micro-site with favourable soil conditions for establishment (Malcolm and Allen 1981).

An M-shaped mound into which seed is placed is formed by the niche seeder. The mound is formed over a deep rip line by opposed discs and a V-shaped niche is pressed into the ridge. The seed is not scattered along the valley of the mound but placed in dollops and covered with vermiculite mulch and then sprayed with a coating of black paint or bitumen emulsion.

The principle of the niche is to ameliorate the soil in the immediate vicinity of the establishing plant. Components of the niche are designed to modify the soil environment.

The V-shape of the mound harvests water to:

- increase salt leaching from the soil around the establishing plant; and
- improve the moisture relations.

The vermiculite mulch above the seed:

- reduces salt accumulation in the soil surface by capillary action;
- improves moisture relations around the seed; and
- does not reduce emergence as with other mulches.

The seed and vermiculite form a placement which is sprayed with bitumen or black paint. This stabilises the placement against wind and water, and increases the soil temperature (Malcolm et al. 1982).

Commercial operators do not use the coating due to the increased cost and impracticable nature of application.

The raised mound on which the seed is sown:

- reduces waterlogging; and
- promotes leaching of the salt.

The deep ripping beneath the mound:

- improves leaching of the salt; and
- promotes root penetration.

The development of niche seeding has improved the establishment of *Atriplex* on saline soils. However, establishment is still considered unreliable with very variable results within paddocks and between seasons, but it remains the best technique available at present.

Acknowledgments

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Establishment and Growth of *Atriplex amnicola* Planted in Different Seasons and at Different Heights on the Sides of Raised Banks

T. Mahmood, R.H. Qureshi, M. Aslam and M. Qadir*

Abstract

Two-month-old seedlings of *Atriplex amnicola* were transplanted at three different heights; ground level, 10 cm and 20 cm above ground on the side of an A-shaped ridge during summer, winter and spring. Canal water (EC = 0.27 dS/m) was used for irrigation. Summer planting resulted in greatest mortality. Winter transplanting at 10 cm gave best establishment and maximum growth.

PAKISTAN is situated mostly in the arid/semi-arid subtropics, with an annual rainfall which ranges from 1000 mm or more in the northern mountainous regions to about 90 mm in the south.

In lowland areas, soil salinity and sodicity are the major agricultural problems. It is imperative that productive use is made of a major part of the salt-affected lands in Pakistan (Qureshi and Mahmood 1990) by growing salt-tolerant trees and forage species for fuel and forage purposes. Suitable species include *Leptochloa fusca* (Malik et al. 1986), *Sesbania aculeata* (Evans and Rotar 1987), *Leucaena leucocephala* (Tomar and Gupta 1989), *Acacia* spp. (Marcar 1989), *Prosopis*, *Eucalyptus* (Qureshi et al. 1990) and *Atriplex* and *Maireana* species (Malcolm 1989).

Among the *Atriplex* species, *Atriplex amnicola* has great potential because of its high salt and drought tolerance. It is a particularly good forage for sheep, as it is palatable and recovers well from grazing (Runciman and Malcolm, 1989). There has been no previous study in Pakistan to identify the optimum environment to plant. Further, the results are also greatly affected by both the time of planting and the planting position of seedlings on the side of a ridge furrow system. Accordingly, this study describes the effectiveness of different planting times and planting heights (on the side of raised banks) for improving the establishment of nursery raised seedlings of *Atriplex amnicola*.

Materials and Methods

The experiment was conducted at the University of Agriculture, Postgraduate Agricultural Research Station, 10 km north of Faisalabad.

Before planting, the site was cultivated and ridged to produce 40-cm-high banks.

Two-month-old seedlings of *A. amnicola* were planted in 5 randomised blocks, each block consisting of 2 replicate rows each of 3 planting heights (0, 10, 20 cm above ground level on the side of raised banks), with 10 plants per row, grown at 3 × 3 m spacing. Planting was carried out three times during the year; summer (May 1989), winter (December 1989) and spring (February 1990).

Eight irrigations (of 8 cm depth of canal water) were applied during the period June to November 1989 for the summer transplanting. For winter and spring transplantings, three and two irrigations of 8 cm were applied respectively, with an interval of one month. The height and crown diameter of 5 randomly selected plants in each treatment were measured at 6 and 10 months to compute the canopy volume. The plants were hand-stripped of leaves and branches less than 3 mm in diameter to determine grazeable biomass. The harvested material was provided to the GOAT experiment of the ACIAR project (see Nawaz and Hanjra. these proceedings).

Plant volume measurements were made at 6, 10, 14, 18 and 22 months from the transplanting date for each planting time.

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Results

1. Climate and Soils

The site was at an altitude of 184 m and experienced maximum summer temperatures near 47°C and minimum winter temperature near 0°C, and had an annual rainfall of 380.6 mm (mostly in the monsoon season, August and September) (Fig. 1). The soil was a strongly calcareous, saline/sodic, sandy/clay loam (EC_e 6.5–52.7 dS/m; pH 8.47–9.85; SAR 24–25).

2. Survival

Seedling survival was lowest for summer planting and highest for winter planting (Table 1), and generally improved with increase in the elevation of the planting position (on the side of raised banks). Lower survival rates at ground level were associated with waterlogging from winter and monsoonal rains (Fig. 1), while deaths at higher planting positions in spring and summer were probably small individuals which became droughted.

3. Productivity

For all planting times except spring there was a delay of 14 months before any significant effect of planting position (on the side of raised banks) on plant productivity was detected (plant volumes: Table 2).

For summer planting, it was only after 22 months that the 20-cm planting position showed significantly greater growth than other treatments.

For winter planting, significant differences existed after 10 months with the 10-cm position favoured over 20-cm and ground level positions.

For spring planting, the 20-cm treatment was favoured over the 10-cm and ground level treatments.

After 14 months, the productivity (canopy volume) of winter and spring plantings were similar, but significantly greater than after the same period of growth for summer planted seedlings.

Very similar results were obtained for mean increase in biomass.

Discussion

The survival and growth of *A. amnicola* seedlings was significantly affected by the season of transplanting and by the position of transplanting on the side of raised banks.

Summer was the poorest season for survival and growth, probably because high temperature, low moisture availability and hot desiccating winds were prevalent during early establishment. Furthermore, summer monsoons brought heavy rains which waterlogged small plants at lower planting positions (ground level and 10 cm) favouring plants at the 20-cm planting position.

Table 1. Effect of transplanting heights on mortality percentage of *Atriplex amnicola* transplanted during three different seasons and at three different heights on the sides of raised banks.

Transplanting heights	Plant survival (%) (after transplanting in different seasons)		
	Summer (May 1989)	Winter (December 1989)	Spring (February 1990)
Ground level	51 ^a	82 ^a	88 ^a
10 cm	67 ^b	96 ^b	97 ^b
20 cm	79 ^c	96 ^b	66 ^c

Means with different letters in a column differ significantly.

Table 2. Volume (m³) of plants at different positions (0, 10, 20 cm) on the side of raised banks planted at different seasons (summer, winter and spring).

Transplanting heights	Summer		Winter	Spring
	14 months	22 months	14 months	14 months
Ground level	3.69	14.97 ^b	4.11 ^b	2.93 ^b
10 cm	2.76	14.64 ^b	5.28 ^a	4.75 ^a
20 cm	3.56	17.38 ^a	4.58 ^b	5.26 ^a
Mean	3.34	15.64	4.66	4.31
Probability	NS	< 0.05	< 0.05	< 0.05

NS = Non-significant.

Means with different letters in a column differ significantly.

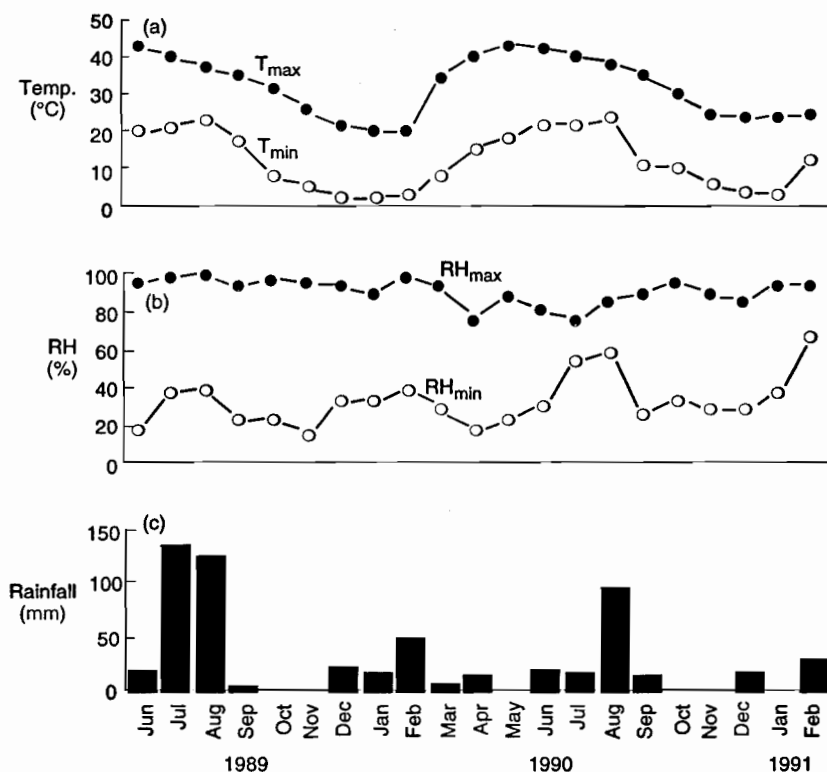


Fig. 1. Annual profiles of (a) temperature, (b) relative humidity and (c) rainfall at the experimental site.

Without the stresses of summer, early growth of winter and spring planted seedlings was more rapid. Winter plantings were well established before the occurrence of summer waterlogging events associated with the monsoon rains, and these larger plants were also less susceptible to drought at the higher planting positions (96% survival).

Spring plantings showed similar survival and growth patterns to winter plantings except, being smaller, they were more susceptible to drought and possibly salt accumulation (66% survival) at the highest planting position (20 cm).

Therefore, the best combination was winter planting at 10 cm above ground level on the side of raised banks.

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Ecology and Physiology of *Atriplex*

Limits to the Productivity of *Atriplex* in Salt-affected Duplex Soils

N.J. Davidson,*† R. Galloway* and G. Lazerescu*

Abstract

Low productivity (0.2–1.0 t/ha) was obtained for *Atriplex amnicola* in salt-affected shallow duplex soils at Tammin, Western Australia. The main contributing factors were the shallowness of the sandy surface soils, the density and impenetrability of the clay subsoils to plant roots, the extreme heterogeneity in salinity and waterlogging. Generally, there was a strong positive relationship between plant productivity and depth of the sandy A-horizon. Deep sands afforded greater access to water and were lower in EC_e and SAR. However, where subsoil depressions in the clay surface followed development of perched watertables after rain, waterlogging caused stunting of plants despite the presence of a substantial sandy surface horizon.

In Western Australia large areas of salt-affected land (up to 9000 ha/year) have been planted to *Atriplex* to provide forage for sheep. However, the productivity of these stands is generally low (1–2 t/ha dry matter production). This contrasts with the productivity obtained from *Atriplex* stands grown under irrigation in deep alluvial soils in Pakistan (8 t/ha; R. Qureshi, pers. comm.) and USA (12–15 t/ha; Watson et al. 1987). Investigations of the reasons for the comparatively poor production achieved in Western Australia were undertaken.

Excavation of the root systems of *Atriplex amnicola* plants growing on shallow duplex soils at Tammin (200 km east of Perth) showed roots to be confined largely to the sandy surface horizons. Accordingly, a detailed study of the relationship between plant productivity and major soil factors was conducted.

Methods

Within a 1-year-old stand of *A. amnicola*, planted at 2.5 × 2.5 m spacings on Mr Wayne Button's farm at Tammin, two transect lines were established in regions where plant productivity was highly variable.

Along each transect, measurements were made of plant productivity (canopy volume), the topography of

the soil surface (measured using a laser level), the topography of the interface between the sand and loam and the loam and clay horizons in the soil profile (assessed using auger-holes), the soil salinity (electrical conductivity of the saturated soil extract, EC_e) and sodium absorption ratio (SAR), and leaf water potential (measured before dawn on 14/2/1992, using a pressure chamber).

Results

In transect 1 (Fig. 1), the lowest plant productivity occurred at the lowest elevation in the transect, and coincided with shallow surface horizons (loam and sand), high salinity (60–80 dS/m), high SAR (80–100) and low leaf water potentials (less than –4 MPa). Investigation of the clay B horizon at this point showed it to have a high bulk density and excavations of *A. amnicola* plants showed that few roots passed into this clay B-horizon.

Highest productivity of *A. amnicola* in transect 1 occurred where the sandy surface horizons increased to approximately 1 m in depth in what was probably a fossil creek channel. At this point deep sands provide a larger rooting volume for *A. amnicola* plants, soil EC_e and SAR were low, and leaf water potentials were high.

In transect 2 (Fig. 2), results were apparently contrary to transect 1. Plant production was least where the sandy profile was at its deepest, where EC_e and SAR were low and leaf water potentials were high. Although this point

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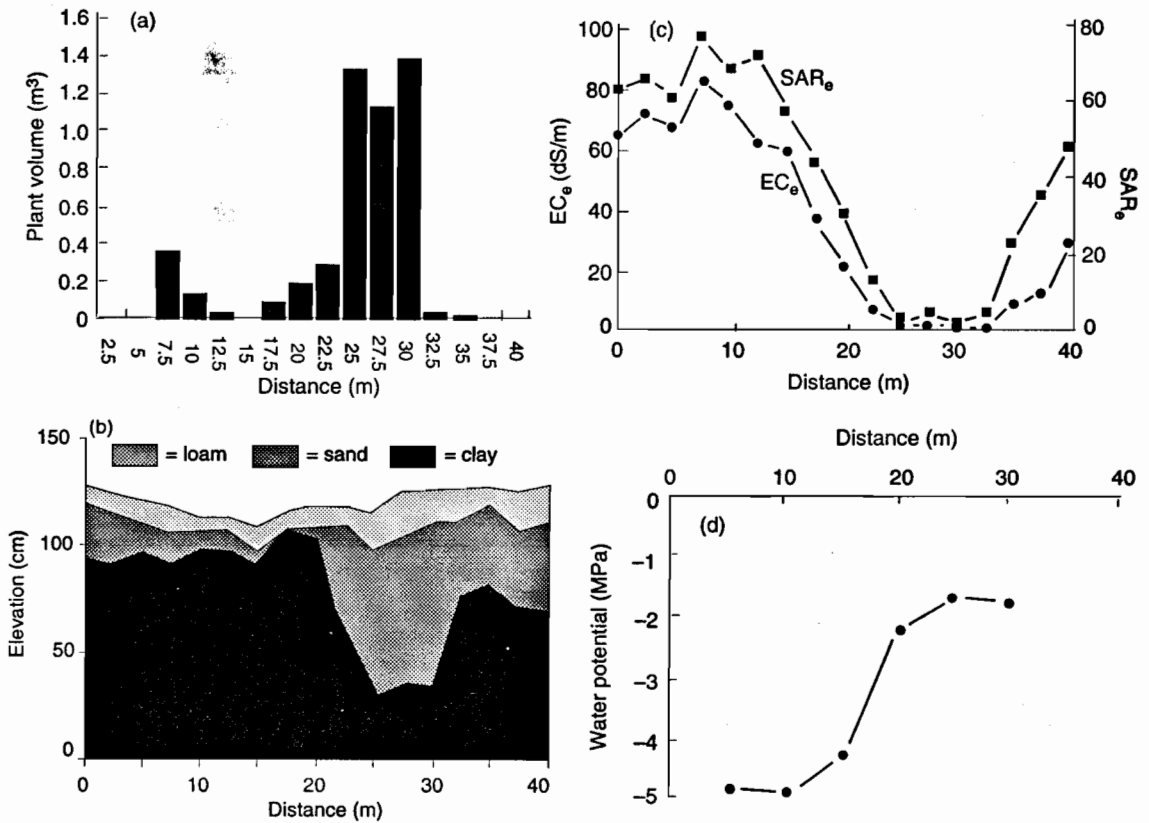


Fig. 1. Transect 1 results: (a) plant volume; (b) topography; (c) EC_e and SAR_e; and (d) water potential.

also coincided with the top of a sandy rise (Fig. 2), beneath was a depression in the interface between the sand and clay horizons of the soil profile, and a perched watertable developed above the dense clay B-horizon after each rain.

Discussion

The surface salinity in salt-affected soils is typically highly variable (Teakle and Burvill 1938). This is caused by heterogeneity in the soil characteristics which influence salt movement (Malcolm 1983), such as micro-topography (Burnstein and Fireman 1957), texture, infiltration (of rainfall; Evans and Levin 1969); capillarity (upward movement of saline groundwater; Talsma 1966), evaporation from the soil surface (influenced by mulching or plant cover; Smith and Stoneman 1970) and macropores in the soil (Nulsen 1980). The results of this study show the growth of *A. amnicola* in salt-affected farmland is strongly influ-

enced by the above factors and by waterlogging. This is consistent with glasshouse studies which show a significant reduction in the growth of *A. amnicola* under waterlogged conditions (hypoxia) and at high salinity. However, the most severe effect is caused by the interaction of these two factors (Galloway and Davidson 1992).

In the field study at Tammin, plant productivity generally increased in response to an increased depth of sand in the soil profile. Deeper sandy surface horizons provided a greater rooting volume and afforded greater access to water in an environment lower in EC_e and SAR. The clay B-horizon was so dense that root penetration was severely limited. Survival and growth of *A. amnicola* in sites with shallow sandy surface horizons depended on penetration of the B-horizons via occasional macropores (old root channels).

Where the interface between the sand and clay horizons was undulating, the depressions in the clay surface developed perched watertables. Waterlogging that occurred at

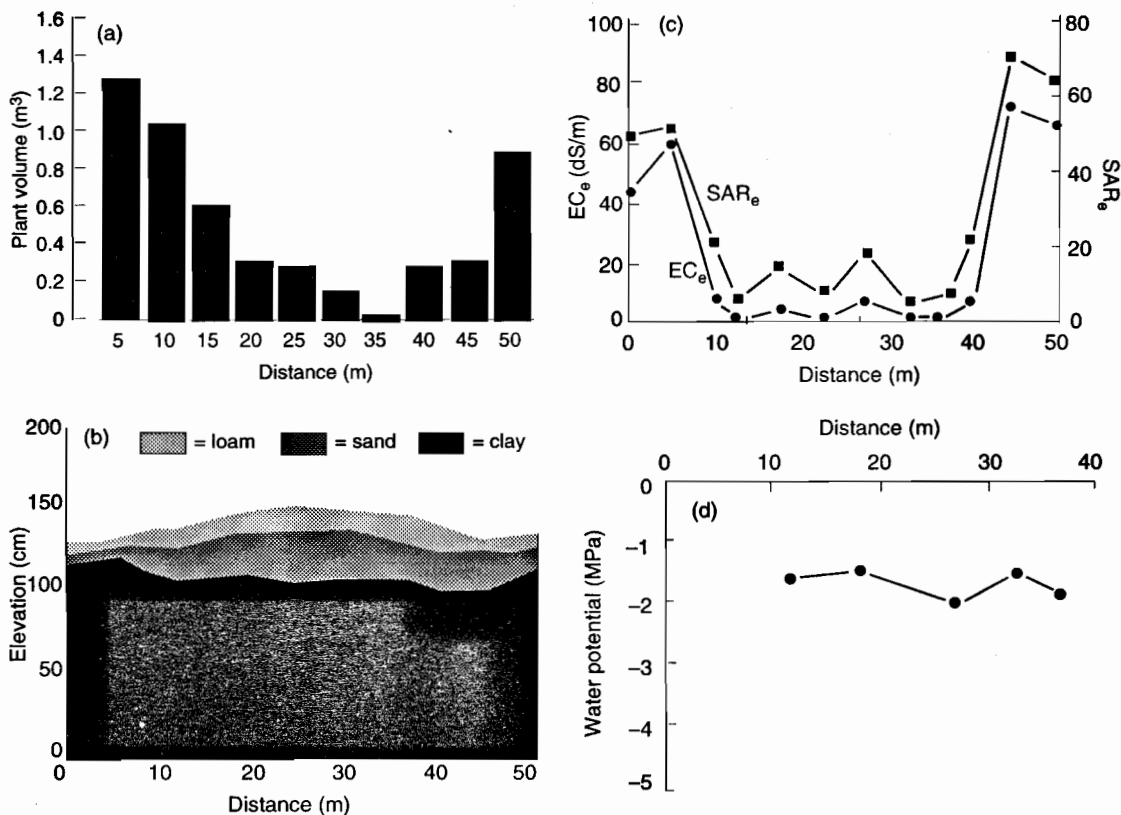


Fig. 2. Transect 2 results: (a) plant volume; (b) topography; (c) EC_e and SAR_c; and (d) water potential.

these sites restricted access to the B-horizon and caused plants to be stunted despite moderate salinity and a more substantial volume of sand for root exploration.

Conclusions

The principal limitations to the productivity of *A. amnicola* on salt-affected duplex soils on the valley floors at Tammin were the depth of sandy A-horizon, the impenetrability of the clay B-horizon, extreme heterogeneity in salinity and periodic waterlogging.

Attempts to raise the productivity of stands by ameliorating soil conditions through deep ripping, mounding or irrigation may produce gains in productivity. However, these modifications are likely to be very expensive and although *Atriplex* is a valuable supplementary feed for sheep in autumn, the returns may not be economic.

The site chosen for this trial was in a severely salt-affected and waterlogged valley floor. Results of this trial suggest that most gains in productivity of *Atriplex*

forage are likely to be made on the mildly affected margins of saltland. Once the problem of waterlogging is controlled by trees, plantations of *Atriplex* could extend onto the valley floor.

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The Interactive Effect of Salt and Waterlogging on *Atriplex amnicola*

R. Galloway and N.J. Davidson*

Abstract

Salt/waterlogging interactions were examined using *Atriplex amnicola* under both field and glasshouse conditions. Both shoot and root growth, biomass, water potentials, stomatal conductance and transpiration were reduced as a result of hypoxia. Short periods of salt/waterlogging (i.e. 1 week) did not have a serious effect on *A. amnicola*, whereas longer periods resulted in an interactive effect detrimental to plant survival, with salt concentrations increasing in the stems and leaves.

THE response of halophytes to low oxygen concentrations and high levels of NaCl are not known. In the case of non-halophytes salt-waterlogging is known to reduce the transfer of oxygen to the plant roots, resulting in anaerobic conditions. Glucose is oxidised to produce only 2 ATP as opposed to 38 ATP under aerated conditions, and the net uptake of Na^{+1} and Cl^{-1} to the shoots is enhanced, resulting in poor growth and ultimately death (Barrett-Lennard 1986; Barrett-Lennard et al. 1990).

The work of the ACIAR program in investigating this interaction is very applicable as *Atriplex* spp. are grown in parts of the landscape subject to waterlogging and high salinity (i.e. valley system depressions). In such environments growth will be limited, and an understanding of the mechanisms at work will allow for the selection of salt-waterlogging-tolerant spp.

Both field and glasshouse trials have been conducted on *Atriplex* spp. Their responses have been examined and will be discussed with particular reference to *A. amnicola*.

Materials and Methods

A field trial was set up at Meckering (140 km east of Perth, Western Australia) using specially constructed plots (4 m × 4 m) using polyvinyl chloride sheeting overlaid on an indurated siliceous pan (see Barrett-Lennard et al. 1986) in which were grown *Atriplex* spp.,

viz: *A. amnicola*, *A. nummularia*, *A. paludosa*, *A. bunburyana*, and *A. amnicola/nummularia* (hybrid cross).

These plots were flooded during summer for four weeks and measurements were made twice-weekly.

Glasshouse trials were also conducted at South Perth using cuttings of *A. amnicola* (971) grown in nutrient cultures at either 50 or 400 mM NaCl. These pots were then either subjected to hypoxic conditions by bubbling nitrogen gas into the system or aerated.

Shoot and root growth, water potential, stomatal conductance, transpiration, dry weight and ion relations (Na, K, Cl) were examined. Plant material was harvested every 2 days during one week, to determine the short-term effects of salt-waterlogging, and weekly over 2 weeks to determine long exposure to salt-waterlogging.

Results

The field trials indicated that tolerance to waterlogging and mild salt (c. 50 mM) was variable. *A. amnicola* performed best over the period of investigation, while *A. bunburyana* the worst. Shoot extensions declined at a similar rate for each spp. The tolerance in decreasing order was: *A. amnicola*, *A. amnicola/nummularia*, *A. nummularia*, *A. paludosa*, and *A. bunburyana*.

Reductions in water potentials were seen first, followed several days later by reductions in stomatal conductance, transpiration and photosynthesis.

Water potentials for *A. amnicola* declined from -2.3 MPa to -2.9 MPa, whereas *A. paludosa* declined from -2.7 to -3.8 MPa. Once plots were drained the shoot

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extensions of *A. amnicola* rapidly returned to those of the controls, while those of less tolerant species remained low. An examination of the root systems showed *A. amnicola* to have a vast shallow root system as opposed to less waterlogging-tolerant species such as *A. paludosa* and *A. bunburyana* (see Fig. 1).

The detailed examination of *A. amnicola* in the glass-house trial showed that the growth of 50 mM aerated plant continued linearly over the period of observation. As would be expected the worst growth resulted from the 400 mM hypoxic treatment (see Fig. 2). There was a 3–4 fold difference in biomass between the worst and best treatments.

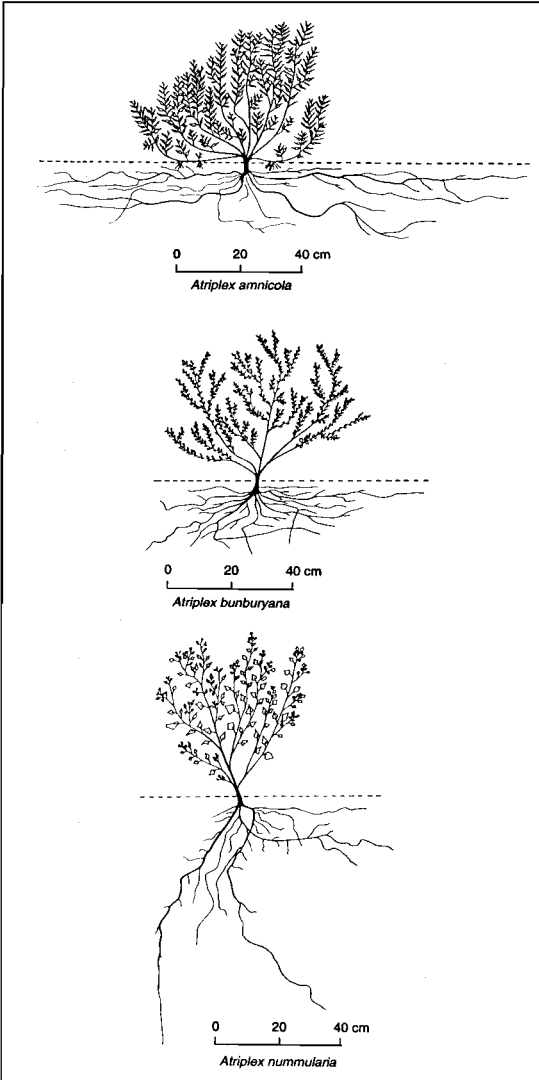


Fig. 1. Diagrammatic representation of *Atriplex* spp. excavated after five weeks of waterlogging.

Root growth ceased with the commencement of waterlogging at both 50 and 400 mM NaCl (see Fig. 3). The roots of 400 mM hypoxic plants became flaccid and translucent and appeared dead, but lateral roots were seen to be developing, and plants had recovered within three to four weeks after the cessation of hypoxia.

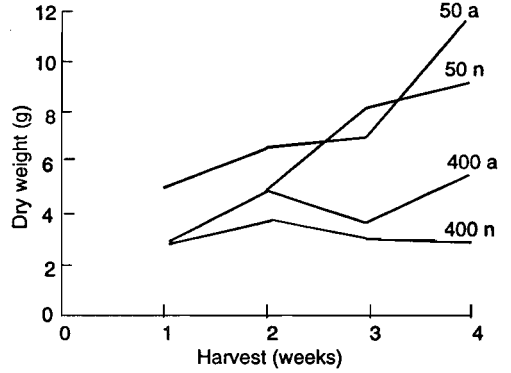


Fig. 2. Plant dry weight of *Acacia amnicola* at 50 and 400 mM NaCl, either aerated (a) or hypoxic (n).

Water potentials differed by -1.15 MPa after two weeks of hypoxia between 50 and 400 mM treatments. Stomatal conductance and transpiration also declined as a result of high salt and hypoxia. After being returned to aerated conditions for one week, water relations had improved, but not to the same levels as aerated controls.

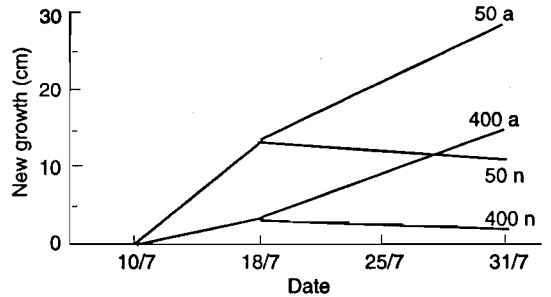


Fig. 3. Root growth of *Acacia amnicola* at 50 and 400 mM NaCl, either aerated (a) or hypoxic (n).

The external salt concentration significantly affected the level of salts within the plant, being highest in the leaves and decreasing in the stem and roots. After two weeks of hypoxia there was a significant result for the interaction of salt and waterlogging. There was a significant loss of K^+ from the roots, whereas the concentrations of Na^+ and Cl^- increased.

Discussion

The overall plant responses to salt-waterlogging are similar for both field and glasshouse trials, though direct comparisons between the two methods should be undertaken with caution (see West and Taylor 1980).

The tolerance of *A. amnicola* to salt-waterlogging can be in part attributed to the root morphology. The rapid recovery of *A. amnicola* in the field plots suggests that the roots were able to resume normal function (as opposed to other species such as *A. paludosa* which is a much more shallow-rooted plant, which does not appear to confer survival under waterlogging conditions) or, as indicated in the glasshouse trial, *A. amnicola* is able to regenerate roots quickly.

Relatively short periods of waterlogging under saline conditions do not produce irreversible trends in ion and water relations. The longer the period of waterlogging the more severe are the physiological symptoms. *A. amnicola* is able to survive up to five weeks of waterlogging under mildly salty conditions during summer (i.e. < 50 mM NaCl). *A. amnicola* responds in a similar

way to non-halophytes to salt-waterlogging, with increased uptake of Na and Cl ions into the tissues (see Jackson and Drew 1984).

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Measuring Soil Salinity in Field Screening Trials for Salt Tolerance

P.G. Slavich*

Abstract

Methods for estimating soil salinity (EC_e) from in situ measurements of soil electrical conductivity (EC_a) are discussed with particular reference to determining salt-tolerance criteria in field screening trials. The four-electrode method, using the Wenner array and insertion probe, and the electromagnetic induction method (EM-38) are described and their applications considered.

The EM-38 can rapidly identify variation in soil salinity (EC_e) at sampling intensities which are not feasible by any other method. EM-38 surveys require interpretation and investigation by strategic soil sampling to determine the nature of the variability. Such surveys can be used to select experimental sites and designs which minimise or take advantage of soil heterogeneity.

EM-38 measurements often correlate well with plant growth and can be used directly as a relative measure of rootzone salinity across most field-scale patterns of soil heterogeneity.

Empirical calibration relationships to estimate the average rootzone EC_e from EM-38 measurements can be developed for most fields using regression analysis of paired EM-38 (EMv and EMh) and soil EC_e measurements. Calibration relationships can also be calculated by combining models which describe the factors affecting EC_a with those that describe response of the EM-38 to profile variation in EC_a . However, empirical calibration relationships have smaller prediction errors than relationships developed from models.

Four electrode methods may be used to measure smaller and more defined soil volumes than the EM-38, as may be required when assessing salinity criteria for successful establishment, or where rooting depths are shallow.

FIELD screening trials are required to evaluate the tolerance of different species or genotypes to saline soils and associated conditions such as waterlogging and sodicity. Plant tolerance to soil salinity under particular environmental conditions may be compared using two major criteria, i.e. the maximum soil salinity for successful establishment, and the rate of decline in growth as soil salinity increases. Field assessment of these criteria requires a suitable range of soil salinity across the screening site or collation of data from a range of sites of varying salinity.

The salinity of soils affected by shallow watertables may be highly variable both laterally and vertically making field screening trials difficult to interpret. It often cannot be assumed that plants growing in adjacent sites are exposed to the same salinity stress. The degree of variability in soil salinity within a particular field is influenced by factors such as the soil formation process,

micro-topography, irrigation history, vegetation cover, watertable depth, and surface soil structure and texture.

The variability in salinity will generally be less in soils developed from flood plain sediments than those from in situ weathering or small catchment sediments. It will also be less across fields with an even slope than those with depressions and rises. Land which has been used for paddy rice is generally less variable than that used under furrow irrigation. Soils maintained under a full vegetation cover are likely to be less variable than that under partial cover. The variation in surface soil structural condition and texture will influence the soil infiltration capacity, water movement within the profile and therefore salinity. The likely degree of variability at a site can be anticipated from a consideration of the above factors before a trial area is chosen for more detailed measurement.

An alternative approach to selecting a site on the above factors is to measure the apparent electrical conductivity (EC_a) of the soil in situ using four-electrode or electromagnetic induction techniques (EM-38). These methods are relatively quick to use and enable large

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numbers of sites to be measured. They have been successfully employed to determine the response of conventional crops to field soil salinity (McKenzie et al. 1983; Slavich and Read 1984; Richards et al. 1987; Slavich et al. 1990; Dunbabin and Slavich 1990).

This paper discusses the application and limitations of in situ measurements of soil salinity with particular reference to determining salt-tolerance criteria in field screening trials. Methodologies to estimate EC_e from EC_a are also considered.

Methods for Measuring Apparent Electrical Conductivity

Measurements of electrical conductivity made on soil in situ, at the actual field water content, are termed soil apparent electrical conductivity (EC_a). Soil EC_a can be measured using two methods, i.e. the four electrode method or the electromagnetic induction method.

The factors which influence EC_a are soil water EC, soil water content, clay content, bulk density and temperature. The EC_a of soil of given texture increases as the soluble salt content and the soil moisture contents increase. Heavy textured soils have higher EC_a than light textured soils with the same soil water EC. The texture effect is partly a moisture content effect, i.e. heavy soils hold more water than light soils and so have more pathways for current flow; and partly due to clay content itself. Clay particles are negatively charged and therefore can conduct a current across their surface while many soil minerals (e.g. quartz, mica, calcium carbonate, gypsum) have no surface charge and therefore act as insulators reducing current flow.

In general the relative importance of these factors on EC_a measurements is salinity > moisture content > surface charge > bulk density. Soil temperature has similar effects on EC_a as on EC of soil:water extracts, i.e. approximately 2.2% per degree Celcius. Soil volumetric moisture content must be greater than 10% for reliable EC_a measurements. There is simply insufficient continuity of current conducting pathways at low moisture contents to enable measurement either by electrodes or electromagnetic induction.

These factors have been integrated into an EC_a model which accounts for the EC of continuous liquid and liquid-solid current flow pathways in soil (Rhoades et al. 1989a). This model is a useful tool for estimating EC_e from EC_a measurements and for evaluating the effects of variation in soil properties on EC_a .

The Four-electrode Method

In this method four electrodes are inserted directly into the soil ensuring electrodes and soil are in close

contact. The two outer electrodes are connected to an alternating current and the electrical resistance (inverse of EC) across the two inner electrodes is measured using an earth resistivity meter (earth tester). The electrodes may be inserted separately at the soil surface at equally spaced intervals in a straight line (Wenner array) or arranged on a probe (10–15 cm long) for insertion into a preformed hole (Shea and Luthin 1961; Halvorson and Rhoades 1974, Rhoades and van Shilfgaarde 1976).

The depth of measurement of the Wenner array is equal to the electrode spacing which is selected by the operator. The variation in EC_a with depth can be determined by taking several measurements at the same site using different electrode spacing. This method is relatively quick as no augering is required, with measurements made in less than a minute.

The four-electrode probe measures a relatively defined soil volume (2.4 L). The probe can be inserted to different depths to determine the depth variation in EC_a . This method requires several minutes per site as a hole must be augered.

The Electromagnetic Induction Method (EM-38)

The EM-38 is a hand-held field survey instrument which measures soil EC_a using the principle of electromagnetic induction. Measurements can be taken within 15 seconds and can be logged to give a continuous trace of soil EC_a .

Soil EC_a can be measured by simply placing the EM-38 instrument on the ground (i.e. coil dipoles orientated vertically EM_v) or by lying the instrument on the ground on its side (i.e. coil dipoles orientated horizontally EM_h). The electromagnetic field of both the EM_v and EM_h measurements penetrate the soil to several metres, but the bulk of the induced response arises from the top metre. The EM_v and EM_h measurements differ in their sensitivity to soil at different depths in the profile. The EM_h measurement is most sensitive to soil near the surface, while the EM_v measurement is insensitive to the soil surface, most sensitive at 0.35 m, and declines in sensitivity below 0.35 m (Fig. 1). The induced response from any depth in the profile depends on both the primary EM field strength at that depth (Fig. 1) and the EC_a of the soil at the same depth.

The EM reading reflects the sum of induced responses from all depths in the profile. Thus, EM_v and EM_h are not simple depth-weighted averages of the EC_a profile, but are averages weighted according to the respective depth response functions. It would be desirable to be able to estimate the depth-weighted average EC_a of shallower intervals (e.g. 0–0.6 m) from EM_v and EM_h . This would

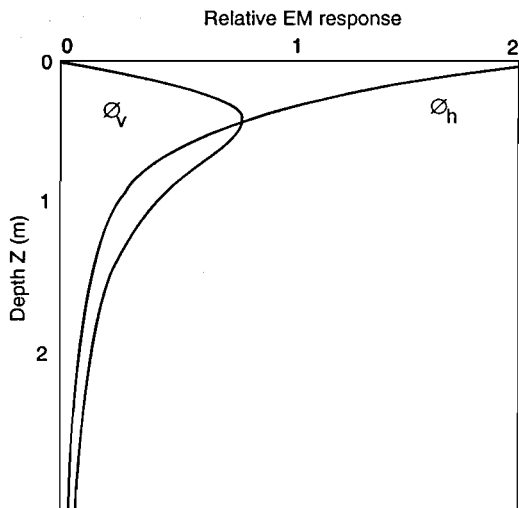


Fig. 1. Relative induced EM field strength at different depths for the vertical (EM_v) and horizontal (EM_h) measurements.

enable EC_v theory (Rhoades et al. 1989a) to be used to interpret EM measurements.

Relationships between EM_a , EM_h and average profile EC_a for depths ranging to 1 m have been developed by modelling the EM-38 response to a representative series of EC_a profiles (Slavich 1990). These relationships, developed from fairly regular and smooth patterns of EC_a profile variations, have been usefully applied to flood plain soils to estimate the average rootzone (0–0.6 m) EC_a from EM_v and EM_h . The following relationships provided a reasonable estimate of EC_a (0–0.6 m) from EM_v and EM_h , i.e.

$$EC_a(0-0.6\text{ m}) = 1.87 EM_h - 0.7 EM_v \quad \text{for } EM_v > EM_h;$$

and

$$EC_a(0-0.6\text{ m}) = 1.24 EM_h - 0.0514 EM_v - 0.11 \quad \text{for } EM_h < EM_v.$$

These relationships may be less applicable to EC_a profiles characterised by abrupt layering as may occur in soils with sharp texture contrast. However, similar relationships could be developed for such soils by modelling the instrument response to likely patterns of variation in the EC_a profile. They could also be developed empirically for a particular field by collecting EM and four electrode measurements (e.g. Wenner array with electrode spacing of 0.6 m) at a range of sites across the field.

Because EM_v and EM_h have different responses with depth, an indication of the distribution of salt in the profile can be obtained by comparing EM_v and EM_h readings. Soil salinity profiles indicating nett downward leaching, i.e. low EC at surface increasing with depth, tend to have EM_v readings larger than EM_h . However, EM_h tends to be larger than EM_v at sites where there is capillary rise of salts to the soil surface, i.e. higher EC at surface than at depth. The greater the difference between EM_v and EM_h , the greater will be the difference between the surface (0–0.3 m) and subsurface (below 0.3 m) salinity.

When using the Wenner array the surface soil must be moist to ensure current pathways through the soil can develop. Useful EM-38 readings can be obtained even when the surface is relatively dry. The Wenner array does have the advantage that the electrode spacing can be varied to alter the effective depth of measurement and that it is not influenced by metal objects, noise from powerlines and magnetic soil minerals, as are EM measurements.

Estimating EC_e from EC_a

While calibration to estimate EC_e from EC_a measurements is not always essential when comparing salt tolerance at a particular site, the form of the relationship should be verified. It also enables across-site comparisons of species performance.

Calibration relationships to determine EC_e from four-electrode measurements of EC_a can be estimated from soil properties or determined empirically for the soil and conditions encountered. The procedure of Rhoades et al. 1989a uses estimates of the soils saturation (or clay) percentage, moisture content, bulk density and temperature to convert EC_a to EC_e . The saturation percentage is the gravimetric water content of the soil paste used to obtain the EC_e extract. The error introduced by estimation rather than measurement of these factors is small (Rhoades et al. 1989b) and acceptable for the purposes of soil salinity appraisal.

The calibration equations in Figure 2 were calculated using the procedure of Rhoades et al. (1989a) assuming the soil was at field capacity and a soil bulk density of 1.5 g/cm³. The figure shows the importance of texture, as indicated by saturation percentage (SP) on the calibration relationship. These equations may yield negative EC_e values at low EC_a . This arises because the relationship between EC_a and EC_e becomes nonlinear for EC_e values less than about 2 dS/m. Although the approach of Rhoades et al. (1989a) has not yet been widely tested outside the USA, it is likely to have general application.

Similarly, soil EC_e can be estimated from EM_v and EM_h using relationships estimated from soil properties

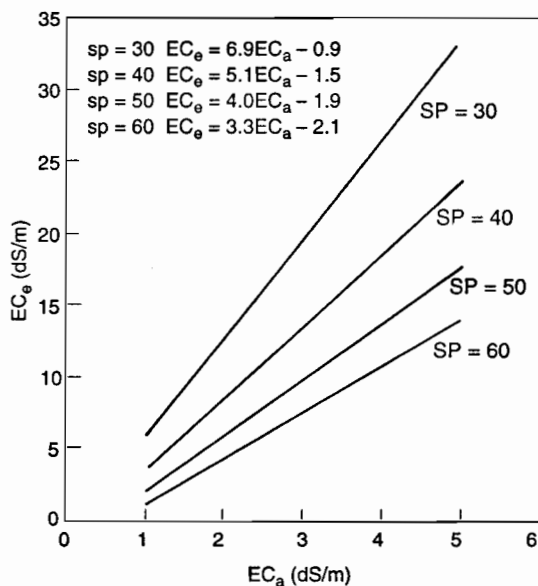


Fig. 2. Calibration equations to estimate EC_e from EC_a measured at field capacity on soils of different saturation percentage (SP). Developed using an approach of Rhoades et al. (1989).

or by empirically determined calibration relationships. Estimated EM calibration relationships for soils of different saturation percentages are presented in Table 1. These relationships were developed by combining the

equations in Figure 2 with those developed to estimate EC_a of particular depth intervals from EM_v and EM_h (Slavich 1990). These relationships were tested using a range of soil profiles of varying texture and salinity. The results (Fig. 3) show that there is generally a fair agreement between measured EC_e and estimated EC_e . The average prediction error (3.2 dS/m) is adequate for classification in terms of low, medium, high and extreme salinity.

Calibration relationships developed empirically from paired EC_e and EC_a (or EM_v and EM_h) measurements are likely to have greater precision than relationships estimated from soil properties. It is usually possible to estimate average rootzone EC_e (e.g. 0–0.6 m or 0–1 m) with an error less than 2 dS/m using a site-developed EM-38 calibration (Slavich and Petterson 1990).

The first step in developing a field calibration is to conduct an intensive grid, (e.g. 10×10 , 5×5 or 2×2 m) survey across the whole trial area. This survey is then used to select 15 to 20 sampling sites which cover the range of variability with even representation of low, medium and high EM readings. It is also desirable to sample across some of the identified small-scale features (e.g. steep gradients, spikes or troughs) in the EM transects in order to determine the soil factors associated with them. Calibration sampling sites should be as laterally uniform as possible. It is desirable that EM readings do not change significantly when the instrument is rotated through 90 degrees on the ground. At each sampling site soil should be collected to approximately

Table 1 EM-38 Calibration relationships estimated for soils at field capacity. Note EM_v and EM_h are adjusted to 25°C from average temperature soil profile.

$$EC_e(0-0.3 \text{ m}) = bvEM_v + bhEM_h + C$$

SP	$EM_v > EM_h$			$EM_h @ EM_v$		
	bv	bh	c	bv	bh	c
30	-6.9	13.4	-0.9	-10.5	17.0	-0.9
40	-5.1	9.9	-1.5	-7.8	12.5	-1.5
50	-4.0	7.8	1.9	-6.1	9.8	-1.9
60	-3.3	6.4	-2.1	-5.0	8.1	-2.1

$$EC_e(0-0.6 \text{ m}) = bvEM_v + bhEM_h + C$$

SP	$EM_e > EM_h$			$EM_h @ EM_v$		
	bv	bh	c	bv	bh	c
30	-4.8	12.9	-0.9	-0.35	8.6	-0.9
40	-3.6	9.5	-1.5	-0.26	6.3	-1.5
50	-2.8	7.5	-1.9	-0.2	5.8	-1.9
60	-2.3	6.2	-2.1	-0.17	4.1	-2.1

0.9 m using 0.15 m to 0.3 m depth increments. It is better to sample the whole depth interval (e.g. 0–0.15 m) than a point from the profile (e.g. 0.15 m). A surface crust of salt should be collected separately (e.g. 0–0.05 cm). The field soil water content profile at the time of sampling should also be determined for each sampling site. This will enable the effect of moisture content to be evaluated. The author's experience is that addition of field water content to the calibration regression as an additional variable rarely gives a significant improvement in the fit. The soils are then analysed for EC_e , saturation percentage and other factors of interest using standard procedures. Regression analysis is then used to develop the best relationship between EM_v and EM_h readings and the EC_e of the depth of interest, e.g. EC_e (0–0.5 m), EC_e (0–0.9 m). A linear relationship is usually adequate for most data, though non-linear calibration relationships may also be present at some fields.

Application of Methods to Field Screening Trials

The EM-38 or Wenner array methods can be used to survey the whole site prior to planting in order to select the most suitable experimental design and to estimate the range of soil salinity present. Ideal sites are those with a wide range of salinity present across a defined gradient. However, saline sites commonly contain some patchiness with high and low salinity zones alternating.

Field screening trials usually require an estimate of soil salinity for relatively shallow depths (e.g. 0–0.3 m) during plant establishment. The Wenner array or four-electrode probe is likely to provide a better estimate than the EM-38 because it can measure a more defined soil volume. If the soil is too dry (less than 10% volumetric water content) soil sampling is the only reliable means of measuring salinity.

Figure 4 shows a comparison of EC_a measured using the Wenner array with electrode spacings of 20 cm and 40 cm with EM_h measured at the same site. The EC_a of both the 0–20 cm and 0–40 cm layers was strongly correlated with the EM_h reading. As sites became more saline the soil salinity tended to increase at all depths, rather than in one portion of the profile only.

During the growth period estimates of average rootzone salinity (e.g. 0–1 m) are required. Several EM readings (EM_v and EM_h) can be collected per plot (or shrub) to provide an estimate of average rootzone salinity. Salt tolerance can then be assessed using regression analysis of yield vs rootzone salinity. This approach has been applied successfully in salt-tolerance trials using barley (Slavich and Read 1984; Slavich et al. 1990). The optimum time for surveys in Australia is during autumn after the opening rains and in spring before the soils dry

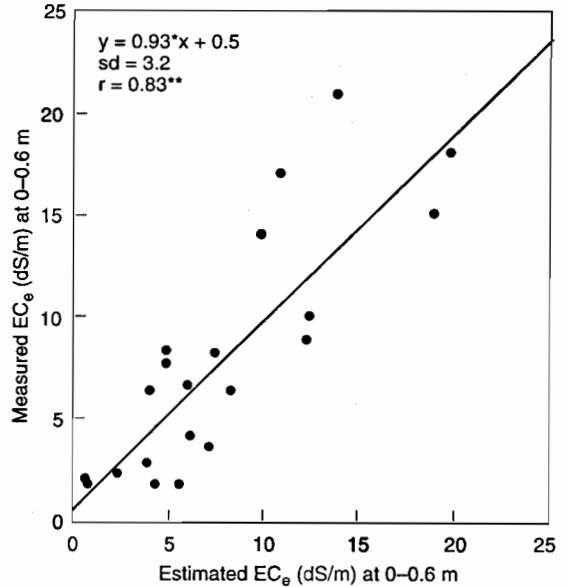


Fig. 3. A comparison of measured EC_e and EC_e calculated from EM-38 measurements using calibration relationships estimated from soil properties (Table 1).

under high evaporative conditions. In Pakistan the optimum times would be immediately after the wet season commences and at the end of the wet season. Such sampling will identify the range of temporal variability which is usually seasonally related. Field variability in soil salinity is likely to make it more difficult to quantify the yield response to salinity of salt-sensitive species than tolerant species. Attempts to establish yield relationships for halophytes have often been unsuccessful using conventional soil sampling. Whether this is due to methodology or the nature of the yield response is unclear.

The EM-38 provides a measure of a volume similar to that of the root systems of many plant species, in contrast to augered soil samples, which may occupy only a small proportion of the rooting volume. There may be significant variation in soil salinity between augered samples (5 cm diameter) within 1–2 m^2 . This small-scale variability is averaged by EM readings. The coefficient of variation of EM-38 measurements is usually less than the EC_e on augered soil samples from the same sites.

It has also been noted that the form by which the EM_h reading integrates the soil profile (Fig. 1) is similar to patterns of root distribution with depth (Rhoades and Corwin 1981). At many times of the year the soil surface (e.g. 0–0.3 m) may be too dry for reliable EC_a measurements but the lower parts of the profile maintained rela-

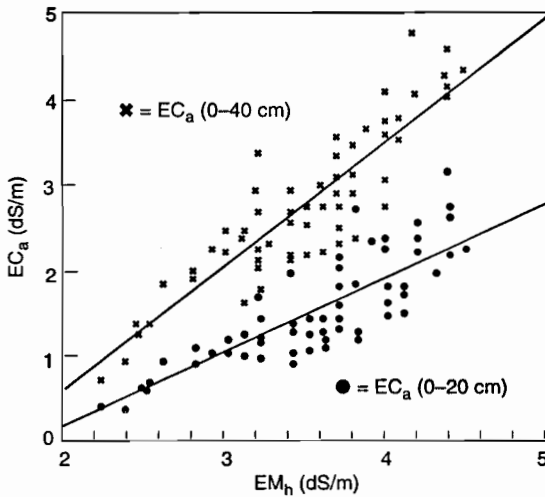


Fig. 4. Relationship between EM_h and Wenner array measurements of shallow depths, i.e. EC_a (0–20 cm) and EC_a (0–40 cm).

tively moist by a shallow watertable. EM readings collected under these conditions will be influenced only by soil layers which have adequate moisture. It is arguable that roots may also be most active in these layers. For these reasons growth may be more closely correlated with EM readings than with EC_e measured on augered samples.

In summary, the most appropriate method for salinity measurement in salt-tolerance field trials depends on the size and variability of the area of interest, the volume of soil of interest and the soil moisture content. EM-38 or Wenner array measurements are best used for large volume (e.g. rootzone 0–1 m) estimates of salinity such as may be required during the growth period. The 4-electrode probe and Wenner array with closely spaced electrode spacing is best used for estimating salinity of smaller defined volumes such as may be required during establishment. Soil sampling and analysis is the only method available when soils have less than 10% water by volume. Soil sampling is also required to estimate or develop EC_a calibration relationship to determine EC_e . The necessity to sample for other soil properties e.g., SAR and pH which may influence the growth response must also be emphasised.

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Concluding Comments

E.G. Barrett-Lennard

In my concluding comments to this ACIAR workshop on the productive use of saline land I want to make a few comments regarding:

- (a) the size of the salinity problem in Pakistan;
- (b) the process of goal setting; and
- (c) some critical factors limiting revegetation.

Size of Problem

Two interesting statistics can be used to define the salinity problem in Pakistan (Qureshi et al., these proceedings):

- (a) the area of irrigated land is about 16 million hectares; and
- (b) most recharge into the groundwater comes from leakage from irrigation canals. The annual recharge from these canals is 43 million acre feet (equivalent to $53.1 \times 10^9 \text{ m}^3$).

If we divide (b), the amount of annual recharge, by (a), the area affected, we can estimate the size of the recharge problem causing salinity. This calculation shows that the amount of recharge over the irrigation area in Pakistan is about 300 mm per year. In other words, we need to develop revegetation strategies which use an additional 300 mm of water per year. It should be stressed that use of this extra water may not be a *difficult* problem, merely an extensive problem. The Australian tree species discussed by Marcar et al. (these proceedings) grow well in Pakistan. Under conditions of lower evaporative demand than found in Pakistan, native forests of these species use up to 1200 mm annually (reviewed in Schofield et al. 1989). Clearly, the widespread growth of such trees in Pakistan would have a considerable impact on recharge.

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Goal-setting

In Western Australia, the area of land subject to dryland salinity has been estimated in six surveys since 1955; during this time the area of previously productive land which has become too saline for conventional agriculture has risen fivefold [from 73 500 to 443 400 ha; cf Burvill (1956) and George (1990)]. Given a continuing of current landuse practices, a further two million hectares of agricultural land are at risk (Anon. 1988). In Australia as a whole there are now more than one million hectares affected (Table 1), although much larger areas than this are clearly at risk.

Table 1. Areas of salt-affected land in Australia and Pakistan.

Country/State	Area affected (million ha)	Reference ^a
<i>Australia</i>		
Western Australia	0.44	1
Victoria	0.39	2
New South Wales	^b	3
South Australia	0.21	4
<i>Pakistan</i>		
	5.7	5

^a References are: 1. George (1990); 2. Government of Victoria (1989); 3. Soil Conservation Service of New South Wales (1989); 4. South Australian Government (1988); 5. Sandhu and Qureshi (1986).

^b This study estimates that 2.2% of the State is affected.

We believe that most of the salt-affected wasteland in Australia is capable of producing some forage, and to this end, the States of Australia have agreed to cooperate in a National Program on the Productive Use of Saline Land which aims to revegetate the salt-affected areas by the year 2000.

In Pakistan there is a area of 5.7 million ha of salt-affected land (Table 1). An agenda for tackling this

problem should also be set. At least some of the major players necessary to initiate and develop such a program for Pakistan have attended this workshop.

Some Critical Factors Limiting Revegetation

The goal of revegetating saltland requires the widest community action. We scientists must be prepared to be part of the community achieving that solution. Revegetation of saltland is ultimately not a task which will be performed by us, but by farmers who believe that by doing so, they will make more money or grow more food. We must develop revegetation technologies, show that they are profitable, and promote their adoption (see scheme in Fig. 1).

I believe that there are two important factors which limit our ability to revegetate saltland. The first is that we tend not to act as members of teams (composed of farmers, extension officers and scientists) dedicated to achieving revegetation (i.e. developing the 'system'). Instead we focus on smaller scientific problems of interest (components of the 'system').

The second factor which limits us is a belief that saltland revegetation cannot be done. The results of this workshop have shown that saltland revegetation in Pakistan is not only possible, but also highly productive.

Conclusion

When we look at soil degradation in Australia, Pakistan, Thailand and India, it is clear that we are observing the loss within a few decades of soils which have taken millions of years to establish. Revegetation of saltland is helping to stabilise these highly erodible soils.

In ACIAR Project 8619 there is a unique opportunity for Australians and Pakistanis to work together to develop appropriate technologies to revegetate saltland. It appears unlikely that ACIAR will fund projects in other countries on this particular topic while this project continues. It is imperative that we make good progress in overcoming the problems facing us and maximising the value of our work to other countries faced with similar problems.

During this workshop, Professor David Sen said, 'The two oldest enemies of agriculture are aridity and salinity'. In this historical context, we at this workshop have the privilege to be coworkers in an activity which could be regarded as a miracle.

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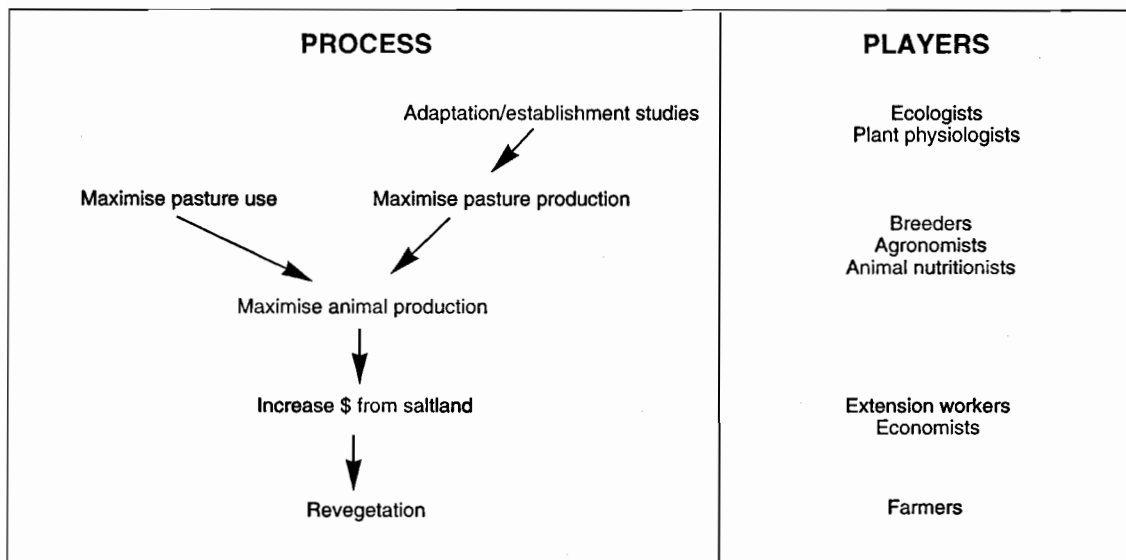


Fig. 1. Schematic diagram of the processes and people involved in developing the technology of saltland revegetation and ensuring its adoption.

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