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Prediction of chloride leaching from a non-irrigated, de-watered saline soil using the MACRO model

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Abstract

A pedon scale study was conducted to investigate the degree of chloride leaching from a de-watered saline soil profile in the non-irrigated wheatbelt region of south-western Australia. Within the surface 250mm of the soil profile was a dispersed layer acting as a hydraulic throttle. Soil water tensions and chloride concentrations were obtained over a two-year period over depths ranging from 0.2m to 1.5m. In the first year the soil surface remained untouched. In the second year, the throttle layer was fractured by ripping to a depth of 250mm. Rainfall, runoff and potential evaporation were also measured at the site. These data were used to calibrate and run the MACRO solute transport model using three surface treatment management scenarios: I. the soil surface remains unchanged ('Do nothing'); II. the soil surface is continually ripped; III. the soil surface is ripped followed by surface sealing. The time period required, effectively, to leach the chloride from the profile, to a depth of 1.5m, was predicted. Effective leaching would take at least 400 years and possibly in excess of 200,000 years for Treatment I, 5 years for Treatment II and 90 years for Treatment III. Macropores that were observed within the sub-surface soil profile played no significant role in the leaching of the chloride. However, the rip fractures were treated as macropores by the MACRO model and as such allowed greater infiltration of water that resulted in the mobilisation of chloride within the rest of the soil profile.

Introduction

In the past 50 years, agricultural production from non-irrigated (dryland) broad-acre regions in south-western Australia has been significantly affected by salinisation. Surface soil salinity has developed as a result of the over-clearing of native deep-rooted vegetation (Peck, 1978; Hillman, 1981; Williamson *et al.*, 1987). Many Australian agricultural soils have a high salt storage but under stable, pristine vegetation conditions the accumulated salts have been maintained in equilibrium. The salinised areas are characterised by groundwater discharge on to the soil surface and associated waterlogged conditions. Management to restore the land for agricultural uses requires that the saturated soil be de-watered either by artificial means in the short term (Salama *et al.*, 1994) or, in the long term, by appropriate vegetation management in recharge areas to utilise the rainfall in the whole catchment more effectively (Bell *et al.*, 1990). The objective of the project reported in part here has been to determine the physical processes of salt removal from salinised soils under natural rainfall conditions once the elevated groundwater level has been lowered.

An initial examination of a number of salinised soils with contrasting texture where pumping had lowered the hydraulic heads to 2m below the soil surface suggested that the salt in the profiles was not being leached (Bourgault du Coudray, 1996). It was evident that the lowering of the groundwater, whilst essential to preventing further development of salinity, was not the only process requiring management. The role of compacted layers and the possible need for soil cultivation and/or amendment to assist leaching required clarification under field conditions. In addition, farmers required information on the time required for leaching to restore the soils to productive agricultural use, so that they could justify investment in management practices.

This paper describes the use of the MACRO model (Jarvis, 1991, 1994) in understanding the role of preferred pathways (Bevan and Germann, 1982; Johnston, 1987; Luxmoore, 1991) in the leaching process and its capability accurately to simulate field measured values of runoff, chloride concentration in the soil solution and soil water tension (Bourgault du Coudray, 1996). The model was then used to predict the time required for infiltration of rainfall to effectively leach chloride from the top 1.5m of the soil profile. Andreu *et al.* (1996) have demonstrated that the MACRO model effectively simulates water and chloride movement in a macroporous soil under irrigated conditions.

Materials and Methods

The methodology involved three stages:

1. A pedon scale field study;
2. A laboratory simulation of leaching in a macroporous system;
3. Modelling of the system based on the MACRO model (Jarvis, 1994).

The groundwater at a salinised field site called 'Wimmera' near Kellerberrin (Mediterranean climate, annual rainfall 350mm), in the wheatbelt of south-western Australia, was lowered 2m below the soil surface by aquifer pumping with a wind-powered pump (Salama *et al.*, 1994). A pedon of area 6m^2 and 2m deep was established at the field site and instrumented with tensiometers and soil solution samplers (Bourgault du Coudray, 1996). The stratigraphic features and soil physical parameters of the site were determined and detailed hydrological measurements of the pedon were made for nearly two years. To enhance leaching, management of the soil at the site was studied in the second year. The soil at the site was salinised and devoid of vegetation.

The soil is a Solonchak formed as a result of in-situ weathering of gneissic granite. The profile consists of a greyish brown sandy loam A horizon with an increase in clay content within the B horizon below 150mm and a C horizon below 650mm consisting of bands of coarse orange or whitish clayey sands interspersed with dark brown bands of heavy clay. The clay at the site is non-swelling.

A dispersed and compacted layer, acting as a throttle to vertical infiltration, was identified at a depth of 100mm. This layer was fractured by ripping to a depth of 250mm on day 518 in the second year of the field study and is referred to as Treatment II. In the model simulations, it is assumed that the fractured surface remains ripped. Field and laboratory observations showed that dispersion caused some sealing of the rip fractures after rainfall. Repetition of the ripping was therefore included as an achievable and practical management option requiring model simulation. This is referred to as Treatment III. With the no-ripping ('Do nothing') management option as Treatment I, three scenarios of management were identified for examination.

DESCRIPTION OF THE MACRO MODEL

The existence of cylindrical macropores (root channels of the original vegetation) and planar macropores (weathered quartz veins) required a model which could simulate the solute flow in a heterogeneous system. The MACRO model (Jarvis, 1994) is a one-dimensional mechanistic model for water and solute flow through soil containing macropores. The model can be used for both conservative and non-conservative solutes and in its simplest form provides a numeric solution of the Richards' and convection-dispersion equations. The chloride ion was the measured solute parameter for the leaching process, with the driving variables for the model being field measured values of rainfall and potential evaporation. The basic features of the MACRO model include:

1. the water balance in the profile, including movement between macropores and micropores, runoff, evapotranspiration, seepage (percolation) and drainage;
2. the interactions occurring at the soil surface;
3. the interactions occurring within the soil profile.

The soil profile is treated as a two domain flow system. The first domain is the soil matrix (or micropore region) where capillary forces within the pore space are assumed to be dominant and solute transport occurs by both convection and diffusion. The second domain characterises the macropores within which water and solute flow is induced solely by gravity (convective flow) with capillarity assumed negligible. The relative saturation of each domain determines the extent of the water and solute interaction between each region.

Macropore flow is generated when the water content in the soil is at or close to saturation (ie $\theta_b < \theta \leq \theta_s$) and the rainfall intensity is larger than the saturated soil matrix hydraulic conductivity. Equation (1) shows the water characteristic curve $\psi(\theta)$ used in the MACRO model, given by the Brooks and Corey (1964) relationship, with $K(\theta)$ determined using the equation of Mualem (1976) and given by the simple power relationship (n^*).

$$\Psi = \Psi_b\left(\frac{\theta_s - \theta}{\theta_s - \theta_b}\right); \quad K = K_b + (K_s - K_b)\left(\frac{\theta - \theta_b}{\theta_s - \theta_b}\right)^{n^*}; \quad \theta_b < \theta \leq \theta_s$$

$$\Psi = \Psi_b\left(\frac{\theta - \theta_r}{\theta_b - \theta_r}\right)^{\frac{-1}{\lambda}}; \quad K = K_b + \left(\frac{\theta - \theta_r}{\theta_b - \theta_r}\right)^{n+2+\frac{2}{\lambda}}; \quad \theta_r \leq \theta \leq \theta_b \tag{1}$$

where θ_s θ_r and θ_b are the saturated, residual and boundary volumetric water contents respectively; λ is the micropore size distribution index; ψ_b is the boundary soil water tension corresponding to θ_b; and K_s and K_b are the saturated and boundary hydraulic conductivity respectively. The word 'boundary' refers to conditions at the interface between the micropore domain and the macropore domain (Jarvis 1994). The boundary water content θ_b is the volumetric water content of the soil after the macropores have drained but the micropores are still saturated; ψ_b is the soil water tension at this point. The boundary hydraulic conductivity K_b is the conductivity measured when the macropores are drained but the micropores are saturated. Soil surface conditions determine the partitioning of water flow between runoff and infiltration into macropores or micropores. If the rainfall intensity exceeds the boundary hydraulic conductivity, water will enter the surface through exposed macropores. When fully saturated layers exist within the simulated soil profile, it is assumed that micropores will not drain or empty until the macropores have drained.

The Richards' equation, as used in MACRO (from Jarvis 1994), is:

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left(K\left(\frac{\delta\Psi}{\delta z}+1\right)\right) - S_r + S_w \qquad (2)$$

where: S_r is the sink term accounting for root uptake of water (not significant at the 'Wimmera' site) and S_w is the source/sink term accounting for water exchange between the macropore region and micropore region; θ is the volumetric water content; ψ is the soil water tension in the micropore region; z is the vertical distance; and t is time. The convection/dispersion equation as used in MACRO (from Jarvis 1994), is:

$$\frac{\delta(\theta c + \rho_b s)}{\delta t} = \frac{\delta}{\delta z}\left(D\theta\frac{\delta c}{\delta z} - qc\right) - U_c - U_d - U_t + U_c \qquad (3)$$

where: ρ_d is the bulk density; c is the solute concentration of the liquid phase; s is the solute concentration of the solid phase; U_c U_d U_t U_e are the source/sink terms for solute uptake by plants, biodegradation, lateral leaching losses to drains/groundwater and mass exchange between the flow domains, respectively. The parameters U_c and U_d are not relevant to the 'Wimmera site'. The dispersion coefficient D is given by the equation:

$$D = D_v v + D_o f^* \qquad (4)$$

Where: D_v is the dispersivity and D_0 is the molecular diffusion coefficient in free water. The impedance factor f^* caters for the tortuosity of the micropores and is dimensionless and assumed constant, whilst v represents the pore water velocity ($= q/\theta$).

SENSITIVITY ANALYSIS

The model sensitivity was qualitatively determined by comparing the accumulated totals for percolation and chloride leaching after running simulations in which each input parameter was varied within its anticipated range, whilst holding all other variables constant. These simulations were conducted using field measurements of rainfall and potential evaporation as driving variables over the time period of 500 days.

CALIBRATION

The input parameters were obtained from measured field values wherever possible. Those parameters that could not be measured directly were obtained from relevant literature sources. The model was calibrated to simulate conditions both before and after surface ripping. Calibration of the model with field data, both before and after ripping, involved adjusting hydraulic parameters to ensure the simulated runoff quantity matched the measured field runoff. The estimated hydraulic parameters were adjusted until field measured values of chloride concentration were simulated within one standard deviation. Further parameter tuning was made to match the simulated and field measured values of soil water tension. When simulating the changes occurring in the field after ripping, only the parameters likely to be affected as a result of the ripping process were adjusted. These included the effective diffusion pathlength, the pore size distribution in the upper soil layers, the saturated hydraulic conductivity, and the degree of macroporosity.

PREDICTIVE MODELLING

Predictive modelling was carried out for the three management scenarios. The treatments were simulated by varying the saturated hydraulic conductivity of the surface layers to a depth of 250mm, this being the depth that would be affected by the ripping action. It was assumed that the physical properties of the soil aggregates remained unchanged with only the degree of porosity increasing to accommodate greater water infiltration. The surface sealing was simulated by lowering the hydraulic conductivity of the surface layers in two stages until the soil had the same hydraulic properties as the non-ripped soil surface. All simulations assumed that the soil was devoid of vegetation. The model was run to simulate 11 years for Treatment II (continuously ripped) and 44 years for Treatments I ('do nothing') and III (ripped with periodic sealing). Eleven years of rainfall and potential evaporation data collected from the nearby town of Merredin (50km east) were used in the simulations. The 44-year simulations for Treatments I and III used the 11-year data replicated four times. Key outputs were plotted to determine the leaching response in each treatment. The best fits to the output data of linear, exponential and logarithmic regressions for Treatments I and III were used to establish the time required to achieve effective leaching. The soil profile was considered to be effectively leached when the profile chloride storage was reduced below 250g m^{-2} at all depths to 1.5m. This was considered sufficient to allow the growth of pastures and crops unaffected by salinity.

Table Model parameters to which MACRO is sensitive.

Parameter	Symbol	Range of values	Output	Sensitivity
Effective diffusion pathlength (mm)	–	2, 50, 100 and 150	TCL	HS
			TCP	HS
Diffusion coefficient	D	1.6×10^{-9}, 4.6×10^{-10}	TCL	VHS
		6×10^{-10}, and 1×10^{-11}	TCP	VHS
Boundary condition at base of profile	–	Constant gradient	TCL	MS
		Constant potential	TCP	LS
Boundary soil water tension (cm)	ψ_b	1, 12, and 50	TCL	VHS
			TCP	VHS
Saturated hydraulic conductivity (mm hr^{-1})	K_s	0.01, 0.1, 1, and 10	TCL	VHS
			TCP	VHS
Hydraulic conductivity micropores (mm hr^{-1})	K_b	0.001, 0.01, 0.1, and 1	TCL	VHS
			TCP	VHS
Pore size distribution index	λ	0.2, 0.5, 0.8, and 1	TCL	VHS
			TCP	VHS
Impedance (tortuosity) factor	f^*	0.1, 0.5, and 1	TCL	VHS
			TCP	NS
Potential Evaporation (mm)	–	using field data,	TCL	HS*
		all values = 0 or 10	TCP	HS*
Number of model layers	–	4, 6, 8, 15	TCL	HS
			TCP	MS
Thickness of top layer (mm)	z_1	10, 25, 50	TCL	HS
			TCP	HS
Mixing depth (mm)	–	1, 5, 10, 20	TCL	LS
			TCP	LS

Notes: TCL denotes total cumulative leaching, TCP – total cumulative percolation, VHS – very high sensitivity, HS – high sensitivity, MS – moderate sensitivity, LS – low sensitivity, NS – no sensitivity.

* The model was only sensitive to the value of potential evaporation when it was set to zero.

Results and Discussion

MODEL SENSITIVITY

The sensitivity of each of the 12 most relevant parameters is given in Table 1. The range of values used is also provided. The sensitivity to some parameters may be a source of error in predicting leaching. An example is the effective diffusion pathlength parameter (see Figure 1), which for the version of the model used, was not adjustable for each soil layer*. Changes in soil texture and structure at different depths may result in changes in the size of soil aggregates. The bigger the aggregate, the longer the effective diffusion pathlength. The longer the effective diffusion pathlength, the greater the total cumulative percolation, with however, a reduction in the cumulative leaching of chloride. In most cases the sensitivity of the model to the values of the parameters listed in Table 1 affected both water and solute transport.

MODEL AND CALIBRATION

The visual comparison between plots of field measured and simulated runoff was good, as shown in Figure 2. The calibration results shown in Figure 3 for chloride concentration at 0.35m is one example that shows the model simulation is within one standard deviation of the measured field values. This is the case over most depths, with the exception being of the C horizon (1.1 to 1.5m) after ripping. Simulated values of soil water tension compared favourably with field measured values (for example, at 0.36m, shown in Figure 4). The processes in the pedon were well simulated by the MACRO model and the selected parameters were appropriate for predictive modelling.

The pedon results obtained before ripping showed that there was no effective leaching in either micropores or macropores. Because of the short-term nature of the field pedon study, the model was used to establish the relative importance of the various pore domains (as defined by

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* The latest version of MACRO (ver 3.1) allows the variation of the value of the effective diffusion pathlength with depth.

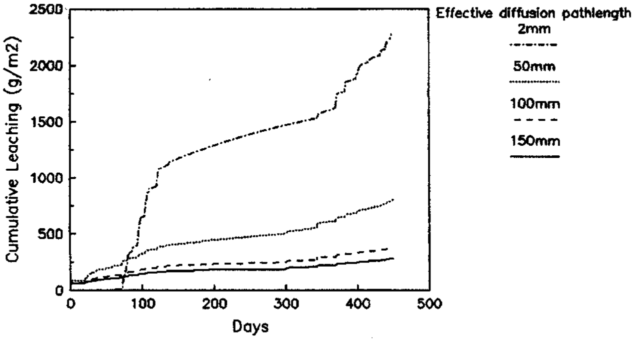

Fig. 1. *The sensitivity to different values of the effective diffusion pathlength on the total cumulative leaching of chloride.*

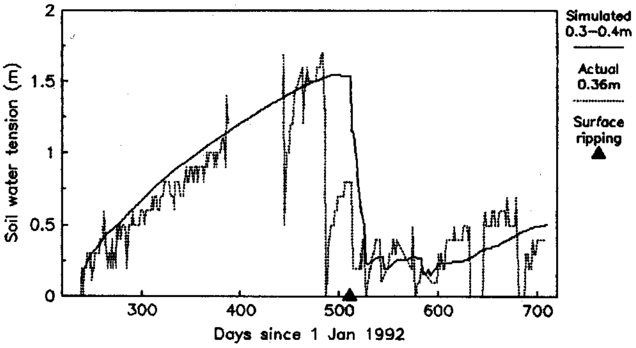

Fig. 4. *MACRO simulated and field measured values of soil water tension.*

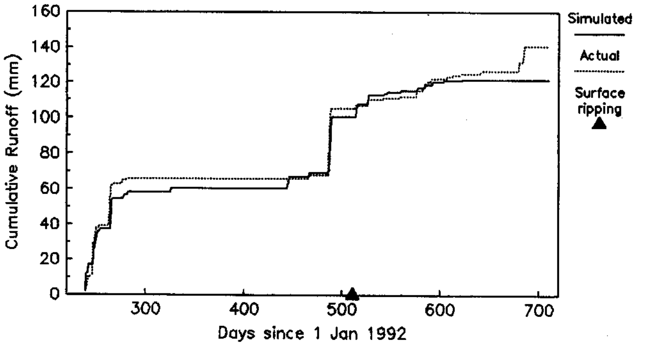

Fig. 2. *MACRO simulated and field measured values of runoff.*

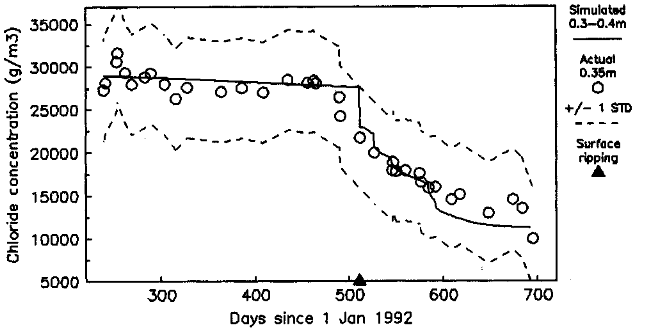

Fig. 3. *MACRO simulated and field measured values of chloride concentration within the B horizon of the soil profile. The dashed line represents one standard deviation either side of the field measured values.*

Luxmoore, 1991) in terms of their effect on the movement of chloride and water within the soil profile. Following ripping of the top 250mm on day 518, most water and chloride movement below the rip fractures occurred in the micropore domain. Macropore flow contributed to the overall movement of water but did not affect the degree of leaching significantly (Bourgault du Coudray, 1996). It could be inferred from the results that mesopore flow may have contributed significantly to both water and solute movement in a similar manner to that reported by Jardine *et al.* (1990).

PREDICTIVE SIMULATIONS

The following points describe the key results from the predictive modelling:

1. Runoff was greatest in Treatment I followed by Treatment III and Treatment II (Figure 5). The rough, continuously ripped surface allows greater water infiltration than the hard-setting dispersed non-ripped surface or the re-sealed ripped surface.
2. The overall profile water storage was greater for Treatment II, followed by Treatment III and Treatment I, with much more fluctuation in values with time in those treatments involving simulated ripping (Figure 6). The greater amount of infiltration into the ripped profile resulted in higher water storage.
3. The chloride leaching rate predicted for Treatment II was much greater than that for Treatment III, followed by Treatment I, in which the rate was almost zero with occasional accumulation occurring (Figure 7). The leaching rate was higher when the soil was ripped as a result of the increased amount of infiltration.
4. The effect of the increase in leaching rate for Treatment II can be noted in Figure 8, where profile chloride storage has been effectively leached (250g m^{-2} to a depth of 1.5m) after 1700 days (~ 4.6 years). However, at this time both treatments 1 and 3 retained chloride in storage of at least 6000g m^{-2}.
5. Curve fitting for profile chloride storage for Treatments I and III was necessary to determine the time to reach the effectively leached condition. The exponential best fit regression (Figure 9) was most appropriate for Treatment III whilst a logarithmic fit (Figure 10) performed best for Treatment I. The r^2 values for Treatments I and III, using an exponential curve, were

0.91 and 0.98, respectively. The number of years to effectively leach, given an exponential extrapolation of the leaching curve, was approximately 400 years for Treatment I and 90 years for Treatment III. The r^2 value for Treatment I, using a logarithmic curve of best fit, was 0.96, and the time required to effectively leach the top 1.5m of profile was in excess of 200,000 years.

6. Macropores (as rip fractures) were found to contribute to the infiltration of water under ripped conditions, allowing the mobilisation of salts in the underlying soil. However, existing macropores within the subsoil had little impact on the transport of chloride. Little water and solute movement occurred through macropores under non-ripped conditions, reflecting the lack of porosity that was observed in the field.

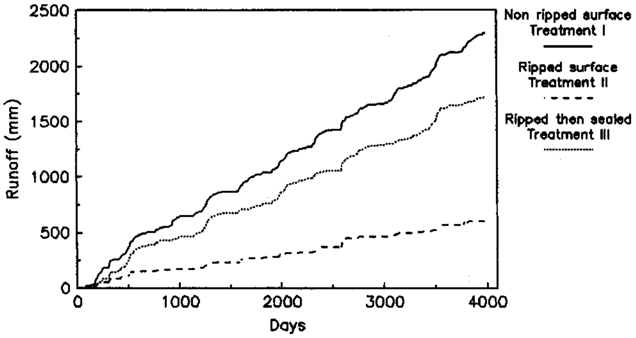

Fig. 5. *Predicted cumulative runoff from the three surface treatment scenarios.*

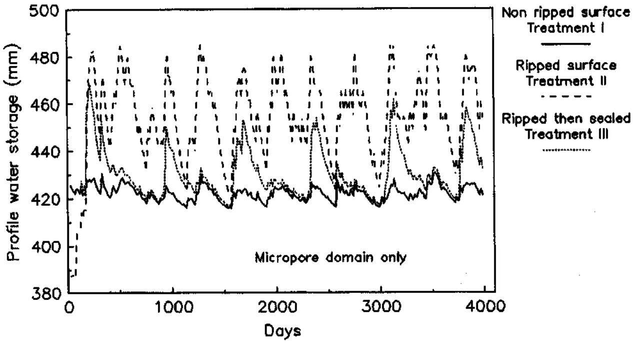

Fig. 6. *Predicted total water storage in the micropore domain from the three surface treatment scenarios.*

Conclusions

Chloride leaching of saline agricultural soils following the lowering of the water table below 2m, in a non-irrigated, low rainfall environment, was well simulated by the MACRO model. The model was run without modifications to any source codes. Predictive modelling showed effective leaching of the top 1.5m of soil profile was achievable within 5 years if the dispersed and compacted

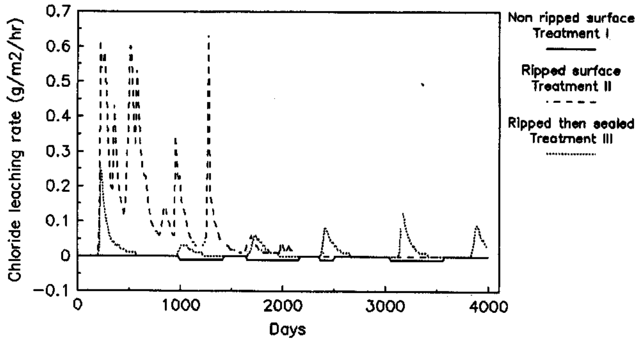

Fig. 7. *Predicted leaching rate from the three surface treatment scenarios.*

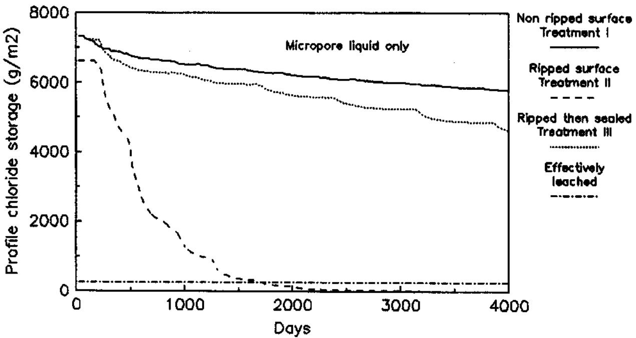

Fig. 8. *Predicted chloride storage in the micropore domain from the three surface treatment scenarios.*

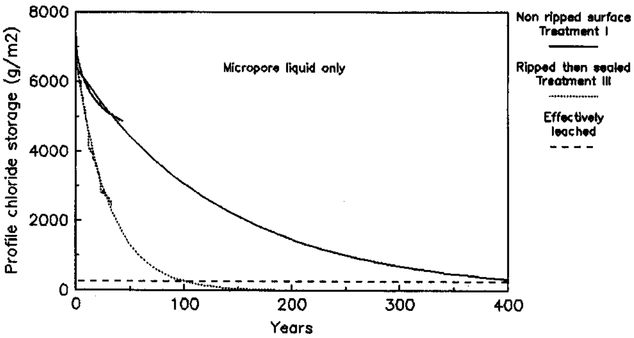

Fig. 9. *Extrapolation of the chloride storage for treatments I and III using an exponential regression line of best fit.*

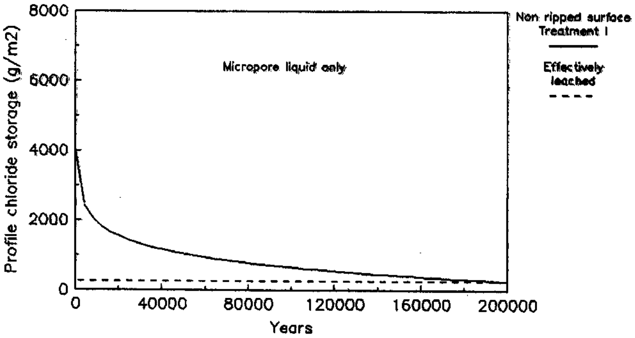

Fig. 10. *Extrapolation of the chloride storage for Treatment I using a logarithmic regression line of best fit.*

soil layers in the surface 250mm of soil profile remained in a ripped condition (Treatment II). Field observations, however, showed that after rainfall the ripped soil aggregates slaked, dispersed and sealed. These effects were not simulated in Treatment II. For the 'do nothing' management option (Treatment I) the simulations showed that greater amounts of runoff occurred and leaching was extremely slow. The third scenario (Treatment III) accounted for the field observation of surface sealing of ripped soil following rainfall and its effect on water infiltration and chloride leaching. The simulations showed that effective leaching, to a depth of 1.5m, would take up to 100 years. This is about six times longer than the time it has taken for similar soil types to become saline in the wheat-growing regions. However, with improved soil and groundwater management, and the use of chemical soil amendments, this time period may be reduced towards the four years predicted for the continuously ripped treatment. It would be feasible (but perhaps difficult and expensive) for farmers to programme the regular ripping of salinised areas into their work schedules.

Existing macropores played no significant role in the leaching of the chloride from the salinised profile. However, the rip fractures are treated as macropores by the MACRO model and as such allowed greater infiltration of water, resulting in the mobilisation of chloride.

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