SCENARIO FOR DRYLAND SALINITY

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ABSTRACT

This paper discusses common perceptions as to the cause of dryland salinity that have constrained the direction of research, and the development of solutions. Issues addressed include the source of salt, and the significance of groundwater. Factors affecting the surficial water balance are identified and examined in the light of changes that can be caused by dryland agriculture. These include rates of water use by different vegetation, and the patterns of movement of water through soils. It is concluded that dryland salinity is caused by soil degradation due largely to a loss of organic matter changing the pattern of water movement through soils. Decrease in the water use through vegetation degradation exacerbates the adverse salinity outcomes.

INTRODUCTION

The currently accepted model for the cause of dryland salinity relates to the uprising of groundwater on the plains due to enhanced accession of water on the hills. The increased accession of water is attributed to tree clearing due to an assumed greater water use by trees than grasses. Some obvious difficulties with this general model are the occurrence of dryland salinity without the occurrence of a water table, and the ability of grasses to use as much water as trees. Another is the need for confinement of water flow from aquifers. It is unclear why, under the defined constraints, the aquifers were not full prior to the initiation of dryland agriculture.

A review of salinity in soils and streams by Peck (1978) identifies that dryland salinity arises through causes such as lateral seepage as well as rising groundwater. The model given in the Australian Dryland Salinity Assessment 2000 as being applicable to all dryland salinity is therefore not general. The information provided by Peck (1978), and more recent studies, indicates a need to further examine the cause of dryland salinity.

This paper addresses the movement of salt in soil within vegetated systems by examining the plant / soil water balance. Consideration is given to the effects on realised outcomes of factors that can be modified by land use. In particular, the hypothesis that salt is mobilised solely by uprising groundwater is contrasted with the hypotheses that most dryland salinity arises through lateral water and salt flow in the soil. With uprising groundwater the causal factor in dryland salinity is a decrease in water use by vegetation. With changes to lateral flow the causal factor is a change in soil structure.

DRYLAND SALINITY

Dryland salinity is taken to be an increase in surface soil salinity associated with dryland agriculture. The social issue relates to adverse changes in the spatial distribution of sodium chloride (NaCl) associated with land use.

Adverse effects of NaCl on vegetation can arise directly through toxicity and osmotic reduction in water availability, and indirectly through changes to the soil structure. It is in these soil structural effects that NaCl mainly differs from other salts that can be commonly abundant, such as lime and gypsum. Calcium in lime and gypsum has a beneficial effect on soils by promoting the aggregation of clay. The mono-valent sodium disperses clay, degrading soil structure and reducing the permeability to water and air.

NaCl is highly soluble, hence its distribution in the soil and patterns of movement are closely linked with the patterns of water flow. Patterns of calcium are also related to water movement, but the rates of change are much slower than for NaCl, and they are much less affected by changes in land use.

The patterns of NaCl can affect as well as be affected by the water balance, as the NaCl changes the soil permeability and plant function. This allows the development of a positive feedback whereby changes to soil salinity can promote further change. This potential for positive feedback applies equally to adverse and beneficial changes.

Origin of NaCl

Salt can derive in soils through the weathering of rock and atmospheric accessions. However, NaCl is highly soluble, hence current distributions need not reflect the origins. Current distributions of NaCl can relate to its transport and modes of accumulation rather than its source.

The main movement of salt is from weathered rock on the land to the ocean, and the ocean is the largest reservoir or salt store. However, there are localised salt stores on land. At a macro level (regional), salt stores can be associated with deep weathered profiles, evaporation basins, or uplifted marine sediments. At a local scale (hill slope), the salt stores are determined by water use by vegetation and vertical and lateral flows of water in the soil. High soil salinity can arise in areas receiving lateral water flows if they have low rates of drainage. Such areas can have low surface soil salinity due to water use by vegetation, but sub-soil salinity in native woody vegetation can be higher than on a coastal, hyper-saline marine mudflat (Tunstall et al., 1998).

Salt can be introduced into a system through aeolian accession, but the rates of accumulation are low except for the immediate coastal fringe. The low rate of accession does not necessarily mean that accumulations cannot be significant as low rates over a long period can produce large accessions. However, accession has to be balanced against losses through leaching. The areas receiving highest aeolian accessions of salt typically have low soil salinity due to leaching by rainfall.

Some identify that near surface salt stores have arisen from in-situ weathering (Gunn, 1985) while others suggest they are largely determined by aeolian accessions (Evans, 1998). Others identify the likely magnitude of the different sources (Creelman et al., 1995), and suggest that current inputs from weathering are not less, and can be up to ten times those from aeolian accessions. However, rates of aeolian accession have been much higher in the past than at present (Butler and Churchward, 1983), hence current rates of aeolian accession may not provide a true indication of the relativities.

Soil salinity exhibits marked variations within regions associated with geological formations, and this indicates a dominance of weathering relative to aeolian accession in producing salt. However, patterns of aeolian accession of clay can be superimposed over the geological formations, indicating that aeolian accessions can be significant. These aeolian accessions of calcium still affect accumulation of NaCl, but the effect is to reduce the levels by promoting leaching. Calcium increases the permeability of soil by aggregating clay, and hence promotes leaching of NaCl.

This effect of calcium on the retention of NaCl illustrates that the significance of aeolian accession of NaCl depends on geology as well as climate. The geology affects the retention of salt making it difficult to separate the effects of weathering and aeolian accession. There can be no simple relationship between aeolian accession and either salt stores or dryland salinity.

It would be difficult to demonstrate either that soil salinity is primarily due to aeolian accession of salt, or that aeolian accession has not significantly affected salt stores. However, there are large differences in salinity within regions associated with geological formations, and current aeolian accessions do not influence changes in salinity associated with land use.

The differentiation between accession of salt through aeolian deposition or weathering is of little consequence in considerations of dryland salinity. The prime issue for land management is the magnitude and location of salt stores, where these are essentially unrelated to current patterns of aeolian accession. The issues in developing understanding are to identify how accessions of salt naturally accumulate in the soil and regolith, and how the accumulation and movement are affected by land use.

Water Balance

The development of dryland salinity is linked with hydrological changes associated with land use as the movement of salt is linked to the movement of water. Changes in salinity are associated with changes to the water balance, where the water balance is determined by surficial processes. These processes are driven by climate, but are moderated by the vegetation and the surface 1metre (approximately) of soil.

Water use by Vegetation

The general water balance in areas subject to dryland salinity has most rainfall being evaporated from the land where it falls. Some of this water evaporates directly from the plant leaves and soil surface (10 to 30% of rainfall), but most enters the soil and is evaporated through plant leaves (transpiration) and the soil surface. The surface run-off and percolation components are generally small, and evaporation is roughly an order of magnitude greater than surface runoff, and one to two orders of magnitude greater than percolation in areas subject to dryland salinity.

The amount of percolating vertically through the soil profile into a groundwater system is estimated through water balance, or from hydraulic gradients and estimated soil permeability, as there are effectively no instruments that allow direct measurement. The absolute magnitude of percolation in areas subject to dryland salinity is usually uncertain as its magnitude is usually small compared with errors in measurements of variables used for its estimation.

Trees vs grasses

The potential rates of water use by different vegetation types vary with factors such as canopy roughness, but the realised rates are largely controlled by the plants in regions where water availability is significantly less than evaporative demand. The rates of water use by native grassland (*Themeda triandra*) with water being readily available need only be 30% & 50% of the evaporative demand in winter and summer respectively (Dunin & Reyenga, 1978). Vegetation tends to regulate water use so as to allow survival during extended periods without rain.

Plants tend to optimise CO2 gain relative to water loss and so reduce water use under conditions of low humidity, but they also reduce water use when not actively growing. Plants tend to maximise the benefits obtained from their use of water. The assumptions in most water balance models used to address dryland salinity, that the potential for plants to evaporate water is proportional to leaf area, and that the relationship between maximum evaporation and potential evaporation remains constant, are incorrect.

The realised difference between water use by different vegetation types depends on complex interactions between the amount, distribution, and intensity of rainfall relative to the area, arrangement, and physiological activity of leaves, soil depth and texture, and plant rooting characteristics. There need be no difference in water use between grassland and treed vegetation in areas of low rainfall and/or on heavy clay soils. However, trees have a higher potential for water use on coarser textured soils than grasses, particularly in areas of higher rainfall.

These water use characteristics reflect natural vegetation patterns, with grasses dominating on heavy clay soils. In general, differences in evaporation from different vegetation types in semi-arid environments are small as the intermittent rainfall inputs are buffered by soil storage, and rainfall is considerably less than potential evaporation.

The above discussion is largely academic when considering dryland salinity in Australia as virtually all grassland is grazed. That is, the potential for the grasses to evaporate water is consistently, and often dramatically, reduced by grazing, as is the interception of rainfall. As the foliage of the woody vegetation is deemed to remain intact, it is essentially axiomatic that treed vegetation will use more water than grazed grassland systems.

Water movement through soils

The pattern of water movement through soils is essentially determined by the water potential gradient and the resistance to flow, where the water potential gradient depends on factors such as soil moisture, salinity, and elevation. The resistance to flow is primarily determined by soil structure, with coarse sands being highly permeable, and heavy clays highly impermeable.

Soil structure is not uniform. Clays develop cracks, root channels form with the death and decay of plant roots, and soil profile development often results in the development of an impermeable B horizon under a relatively permeable A horizon. Soils usually exhibit pronounced horizontal layering, with large differences in permeability between layers.

The layering in soils is largely a consequence of water use by vegetation. Rainfall entering the soil surface flushes salts and clay down the profile. The withdrawal by plants of low salinity water from depth helps prevent this salt from moving back up the soil profile. It also limits percolation, and hence flushing of salt through the soil profile. In effect, a cycle develops whereby water use by vegetation allows rainfall to continuously flush salt and clay down the profile and cause it to accumulate in the subsoil. The depth of flushing depends on the depths of rainfall penetration and plant roots, where the penetration of rainfall depends on soil properties as well as the amount and temporal distribution of the rainfall.

The leaching of salt from the surface soil and accumulation in the subsoil is normal in vegetated systems. The simple occurrence of surface leaching does not differentiate increased or decreased rates of recharge as suggested by Evans (1998). Such leaching occurs in a brigalow forest growing on a saline marine sediment in a semi-arid region where there is effectively no deep drainage (Tunstall and Connor, 1981). One consequence of this surficial leaching of salt for considerations of salt accession is that surface erosion preferentially removes non-saline material.

The occurrence of preferred pathways strongly influences patterns of water movement. Water moves rapidly down cracks and old root channels. In the brigalow system identified above the flow of water down cracks in depressions reinforces the development of the gilgai formation by flushing salt laterally. Most salt is stored under mounds.

The effects of preferred pathways are difficult to quantify, particularly for cracks, as they vary rapidly over space and time. Average measures and steady state models have limited applicability.

Movement of salt in soil by water

As the distribution of NaCl is related to the movement of water, the development of dryland salinity relates to changes in the pattern of water movement associated with land use. Factors that affect the patterns of water movement are:

- The permeability of the soil.
- The occurrence of preferred pathways such as cracks in the soil, old root channels, geological fault lines, paleo drainage systems.
- Changes in vegetation.

Of these, soil permeability, cracking, drainage through old root channels, and vegetation development can be affected by land use.

Salt naturally accumulates in soils in areas with limited percolation of water through the soil, and the depth of accumulation depends on the soil properties, the characteristics of the rainfall, and the vegetation. Decreasing the permeability of the soil and/or the depth of extraction by plants results in salt moving closer to the surface. Because of the potential for direct evaporation of water from the soil surface, and the depth of penetration of a given amount of rainfall, the potential for salt to move upwards is higher for clays than sands.

Reducing soil salinity, and promoting the movement of salt required to cause dryland salinity, requires percolation of water through the soil. However, percolating water need not remove salt as clays can adsorb salt from water (Blackmore, 1976).

The general situation appears to be that water flowing through soil increases in salinity if only because of the uptake of essentially pure water by plants, but that the salinity of the percolating water is not in equilibrium with the general soil salinity. The salt concentration in water flowing through the soil tends to be less than the salt concentration in the bulk of the soil (Peck, 1973). This arises because water tends to flow through preferred channels, such as cracks and old root channels, and does not come in contact with the bulk of the soil. As diffusion of salt from the bulk of the soil to drainage channels is slow, water flowing through the channel can have low salinity compared to the salinity of water in the surrounding soil.

Large amounts of salt cannot accumulate where appreciable amounts of water drain through the soil. Dryland salinity is therefore associated with situations where the rainfall is less than the evaporative demand, and where the soil profile and/or underlying structures limit the drainage of water. Coarse sands are rarely saline regardless of the climate.

Preferred pathways

The flow of water through preferred pathways decreases the uptake of salt by the water, and hence decreases the salinity of water outflows. Loss of preferred pathways, as occurs with soil structural decline, reverses this effect. The percolating water comes into closer contact with the bulk of the soil, and its residence time is increased. This results in the salinity of water flowing through the soil tending to come into balance with that in the bulk of the soil. That is, soil structural decline tends to increase the salinity of percolating water.

The pathways for water movement depend on the structural characteristics of the system. With duplex soils the main pathway will be along the surface of the B horizon. In deep sands the main pathway will be vertically down to a water table or impeded layer, with the direction of the subsequent lateral flow depending on the hydraulic gradient.

The structural aspects of systems that affect water movement can be addressed at various scales. At a local scale the soil structure dominates, with factors such as texture profiles, organic matter, cracks, and root channels affecting the response. Landscape effects become prominent when expanding the size of the area being considered, with terrain and layering of soil profiles largely affecting the outcome. However, geological structural features can also be prominent by way of differences in the nature of the materials, and structures such as fault lines and paleo-drainage.

Most water is cycled through the soil surface, and only a small component is relocated in the system. Of the relocated water, overland or surface flow represents the main component, and this generally has low salinity. The next greatest flow is laterally in the surface soil along the top of the subsoil. This water can, but need not, develop appreciable salinity. Moreover, it need not be detrimental in areas receiving drainage as the enhanced water supply can promote growth of vegetation. The realised outcomes depend on climate as well as the characteristics of the soil and terrain, and hence can vary with climatic fluctuations.

The characteristics of the earth that most determine outcomes are embodied in the surface one metre of soil. Also, the land use impacts that produce the adverse outcomes are only applied to the surface metre of soil, and most management actions that can be used for remediation can only be applied to the surface metre. Knowledge of the surface metre of soil is therefore crucial to the development of an understanding of the development of adverse salinity, and is usually essential for developing remedial actions.

CURRENT GENERAL MODEL FOR DRYLAND SALINITY

Dryland salinity is inextricably linked with rising groundwater in the Australian Dryland Salinity Assessment 2000, where groundwater is defined as *All free water below the surface in the layers of the Earth's crust*. This definition is problematical as any water containing salt is not completely free due to osmotic reduction in water potential.

Groundwater generally refers to water that can potentially be extracted by pumping, and hence is observable as a water table. It therefore essentially refers to water held in voids rather than water bound on clay and other surfaces, and effectively has zero matric potential. It does not refer to water retained in soil that has drained to moisture levels below field capacity, and is generally not applied to water in soils held within the rooting depth of plants unless there is a clearly defined and persistent water table.

Groundwater systems, or aquifers, are fed by water percolating through the soil, but such water also feeds streams and can seep to the soil surface. Percolation of water through the soil includes lateral as well as vertical components, and none of the percolation need contribute to groundwater systems.

Aquifers can drain into streams but the rate of drainage depends on the structure of the system. The structural characteristics of the materials determine permeability to water flow, and most flows occur in coarse sediments or rock fractures. The arrangement of these materials determines how systems function, and features such as layering, faulting, and uplifting can determine the aquifer response. While a wide diversity of materials and structural arrangements is possible, some features are common, and hence are incorporated in groundwater models.

The occurrence of a permeable layer between two layers of low permeability produces a confined aquifer, defined in the Australian Dryland Salinity Assessment 2000 as *Confined aquifers have a layer of rock above them which are impermeable*. For modeling, the lateral extents are usually regarded either as infinite or confined. This can result in the water in the aquifer being under pressure, which is reflected in the peizometric head being higher than the water table. Confined systems can respond rapidly to changes in water input as the changes can be transmitted as a pressure with little flow of water.

While confinement is generally defined as relating to horizontal barriers there can also be vertical barriers to flow. The bucket model for dryland salinity, whereby increased accession of water increases the height of the water table, can only apply where the flow from the system is restricted. The system is therefore assumed to be closed or partially closed. A system where water drains freely is referred to here as being open.

The general groundwater model for the development of dryland salinity suggests that, as a consequence of clearing trees:

- More water percolates vertically through the soil on hills, where this contributes to a groundwater system.
- The additional percolation of water causes the water table to rise under the adjacent plains.
- The rising groundwater under the plains brings salt to the surface.

For confined aquifers the system is said to operate like a hydraulic jack whereby input of fluid in one part of the system raises the water level in another part. For unconfined aquifers the system is regarded as a bucket.

The essential elements for such a system to function, additional to the greater input of water into the soil through percolation, are:

- Connectivity. There must be a channel connecting the water draining vertically through the hills to the water underlying the plains.
- Closure. There must be a barrier to the flow of ground water from the system so that groundwater on the plains cannot drain away and is forced to move vertically upward.
- Salinity. The subsurface material / water on the plains should contain salt.

The generality of this model is difficult to demonstrate as systems that can be subject to dryland salinity need not have definable water tables. Moreover, the small size of many water stores, and/or confinement should result in adverse salinity being clearly evident within a short time of the commencement of agriculture in many systems. The period is identified as generally being less than 10 years for local systems in the National Dryland Salinity Assessment 2000. In effect, the suggested changes to percolation through land clearing would essentially be immediate, and the changes to surface salinity would be rapid in systems where the water table was naturally close to the surface, and/or the aquifer was confined.

Dryland salinity has typically taken around 50 to 100 years to develop thus it is not a direct response to a change in the rate of water use. Other inconsistencies with the model are:

1. No mention is made of increased percolation on the plains, when the model depends on the plains being permeable to water and the plains were the first to be cleared.
2. Outflows from the groundwater system have to be restricted, and rates of outflow are often said to be unaffected by the hydraulic head.
3. Following from 2, it is unclear why the water table was initially at a low level as with the defined constraints any percolation in the hills would naturally result in the water table on the plains rising to where water could be extracted by vegetation.

The general model depends upon water percolating through the hills and, given the variability of rainfall, this would have occurred in the absence of clearing. There has been ample time for aquifers to fill prior to the commencement of dryland agriculture, particularly for local and regional systems. This, and the lack of rapid, widespread development of dryland salinity in local systems indicates that the general model invoking rising groundwater is potentially invalid.

Many alternate models have been proposed to account for discrepancies between observed situations and the circumstances identified in the general model, but they are usually structured around the general model. The need for alternate models derives in part from differences in constraints between systems but it also derives from the assumptions in the general model. Apart from the assumed need for a groundwater system, the generalised model represents a steady state system when the water relations in areas subject to adverse salinity are highly dynamic. The TOPOG model, developed by O'Loughlin (1986) to address soil moisture, and used by Hatton (1999) to address dryland salinity, for example, is a steady state model.

Rainfall is intermittent and generally much less than potential evaporation, hence periods of saturated flows in soils are usually highly sporadic. Application of steady state theory to such dynamic systems can sometimes be useful, but it is theoretically unsound and can lead to incorrect conclusions.

SCENARIO FOR DRYLAND SALINITY

The inability to reliably measure the factor deemed responsible for the adverse change to salinity, namely percolation, means that conclusions as to the cause of dryland salinity depend on logical analysis of the factors causing change.

The essential factors in the development of dryland salinity are:

- Mobilisation of salt in drainage water.
- Accession of drainage water near the soil surface at some point in the landscape.
- Increase in the concentration of salt through evaporation of water.

The increase in the concentration of salt can occur through evaporation across the entire landscape but may be greatest where water discharges.

Mechanism

The uncertainties as to the occurrence of dryland salinity relate to flow paths. There would be no adverse effects on land if the water simply drains from the system, as occurs with drainage into rivers, hence pathways and blockages to flow are crucial.

Sub-surface water flows can be vertical and/or lateral. Vertical flow alone cannot produce adverse salinity of surface soil except, theoretically, in completely confined systems where the pressure is transmitted via a hydraulic connection, and with the bucket model where the system is completely closed. However, even in confined systems the production of surface soil salinity depends on the occurrence of some lateral flow. The occurrence of dryland salinity almost invariably depends on lateral flow.

Water can take several paths in traveling from high to low points in the landscape and the relative flows along different paths relate to the resistances. The resistance to flow is least on the soil surface, and surface run-off generally accounts for most lateral flow of water. This surface flow can produce adverse salinity if the water accumulates and cannot flow out of the system, but any adverse effects are generally associated with waterlogging rather than salinity. The most notable exception is Lake Eyre where accession of low salinity water over a long period has produced high salinity.

The sub-surface resistances to flow vary greatly depending on the nature and arrangement of the material, and the levels of resistance can span many orders of magnitude. Water drains very freely in coarse sands but heavy clays can essentially be impermeable.

Resistances are by far the lowest with pipes or channels and these arise with cracking of soil and the decay of plant roots. The next lowest resistances generally arise with coarse soil textures, such as sand. Resistances generally greatly increase from sands through loams to clays, but the resistance is not just a function of particle size. The structure of clays can vary greatly depending on mineralogy, and aggregation of clay can produce high permeability. Aggregation is promoted by organic matter, and by bi and tri-valiant ions.

While the above is a very broad summary of the soil factors that determine the resistance to the flow of water, it identifies key elements in considerations of the effects of land use. Land use can affect resistances to flow by altering:

- The amount of soil organic matter
- The occurrence of old root channels
- The relative abundance of mono and bivalent ions.

Effects of tree clearing on soil structure derive from the loss of supply of large roots that can form channels, a decline in the input of organic matter, and an increase in exposure of the soil surface to rain and radiation, where the exposure increases the breakdown of organic matter. The effects of grazing are similar in decreasing the input of organic matter and increasing its rate of breakdown. The differences are that grass roots are much smaller than for trees, and grazing can directly cause compaction by the impact of animal hooves. Grazing has a greater impact on the surface soil than killing trees (Tunstall & Webb, 1981, Tunstall et. al., 1981).

Of these effects, those affecting soil organic matter are seen as being of most consequence. Dryland agriculture decreases the input of organic matter and increases its rate of breakdown due to the higher soil temperatures and soil moisture. This produces a marked decline in soil structure evidenced by compaction, which increases the resistance to the flow of water. The structural decline can be promoted by mechanical disturbance such as ploughing.

Tree roots tend to form drainage channels when they decay, but these eventually become clogged by clay. High sodium disperses clay and hence accelerates the clogging of preferred channels. The effects of land use therefore serve to:

- Decrease the rate of flow of water through the soil
- Increase the residence time of water in the soil.
- Increase the extent to which the water flows through the general soil matrix rather than preferred channels.

Water percolating in undisturbed systems tends to have much lower salinity than water in the bulk of the soil through draining rapidly through preferred drainage channels. By comparison, the salinity of water percolating through structurally degraded soil would tend to match that in the soil. In effect, soil structural degradation results in the soil performing as a series of horizontal layers of homogeneous porous media rather than a complex transport system having freeways, feeders, bypasses, and local routes. These changes would combine to:

- Decrease the percolation of water to depth in the soil (decrease deep drainage).
- Increase the control of water flows by soil profile layers (eg. increase flow across the B horizon).
- Increase the salinity of water flowing through the soil compared with the natural system.

An increase in the salinity of the drainage water decreases soil salinity where water is shed but increases salinity in accession areas. The decrease in permeability increases the flow of water close to the soil surface where this is accentuated by any decrease in water use by vegetation.

The main salt transported is NaCl due to its solubility. The accumulation of NaCl in accession areas produces a positive feedback due to its effect in dispersing clay. The accumulation of water in accession areas is initially promoted by the loss of organic matter, but this becomes reinforced by the accumulation of NaCl.

The NaCl promotes the maintenance of high soil water contents by restricting water uptake by plants. This can reduce drainage by limiting the development of cracks, and decrease the effective water storage capacity of the soil profile. While the magnitude of these effects depends on soil texture they reinforce the other deleterious changes. A cycle develops whereby the deleterious changes are self-reinforcing where this promotes the spread of adverse change.

Variations with scale

The general process described above treats soil as being composed of horizontal layers of different permeability, such as a loam surface over a clay subsoil. The system is regarded as being vertically stratified and horizontally uniform. This is only a first approximation as systems show pronounced horizontal variation due to surficial geological factors such as faulting, and paleo-drainage.

The effects of large structural features vary. Underlying aquifers can provide local improvements by improving drainage, but can cause damage elsewhere by adding salt to discharges. In general, transport systems or conduits provide benefits in areas they drain and detriments where they discharge (Trethewey & Gourlay, 2001). Blockages to flow can cause high salinity even in geological formations having low salinity (Tunstall et al., 1998). Functionally the processes do not differ from the general hill slope model described above, and the difference relates to the control by geologic structures rather than surface topography and soil profile development.

The occurrence of several factors in determining realised outcomes illustrates the importance of identifying the structural controls. Knowledge of how systems function can only be usefully applied if information is available that defines the spatial distribution of the controlling factors. The factors generally considered include climate and topography, and 'underlying aquifers', but there has been little consideration of the structural features of the soil. The spatial distribution of soil properties that determine flows is essentially never determined, and near-surface structural features, such as fractures and fault lines, are seldom mentioned.

These conclusions do not suggest that dryland salinity cannot be caused by uprising groundwater. They suggest that the rising groundwater model is a special case of a more general model.

Summary

This explanation of dryland salinity has degradation of vegetation causing a decline in soil structure. This decline serves to:

- Increase the near-surface lateral flow of water by decreasing the permeability of the soil, which increases the accumulation of water in accession areas.
- Increase the salinity of accession water due to increased exposure of drainage water to the soil.

These effects are enhanced by:

- Decreased water use by vegetation, where this increases drainage and water accessions.
- Decreased drainage from accession areas due to $NaCl$ decreasing the permeability of the soil.

The cause of dryland salinity is seen as being a decline in soil structure due mainly to a loss of organic matter, where the salt serves to provide a positive feedback. Areas with low salinity are subject to waterlogging rather than adverse salinity. From a process viewpoint, dryland salinity is a symptom of land degradation rather than the cause.

With this explanation dryland salinity is caused by a change in the pattern of water drainage through soils and hence can arise without an increase in the amount of drainage of water. A decrease in the water use by vegetation can enhance the development of dryland salinity but it is not the cause.

The degradation of vegetation that produces dryland salinity may relate more to a loss of grasses than trees. Trees produce large root channels that provide considerable benefit, but grasses tend to build higher levels of soil organic matter than trees. While the relative benefit of trees and grasses is uncertain, tree killing promotes grass growth, and this growth can compensate for the loss of trees provided the grasses are not heavily grazed. The main land management practices that cause adverse salinity are therefore grazing and farming (ploughing) rather than tree removal.

Climatic Constraints

The prime requirement for the occurrence of dryland salinity is for rainfall to be considerably less than potential evaporation as salt tends to be leached from soil in areas of high rainfall. However, the occurrence of some percolation is necessary for the occurrence of dryland salinity. Dryland salinity can occur without lateral flow of water but most expressions are associated with lateral flow of seepage water.

The soil should become saturated for some period throughout the year to produce significant percolation as flow rates of water are very slow in unsaturated soils. A dry period is then usually required for evaporation to concentrate the salt. Mediterranean climates are therefore most prone to the occurrence of dryland salinity. Situations where rainfall mirrors evaporative demand (no seasonality in water availability) have limited occurrence of dryland salinity. Dryland salinity is promoted by winter dominant rainfall, and militated against by high summer rainfall.

The large fluctuations in rainfall in Australia across years can result in expressions of dryland salinity varying between years depending on seasonal conditions. In some circumstances a period of higher than average rainfall can flush salt and hence improve dryland salinity, while above average rainfall can increase salt accessions in other environments. Increasing the flow rates through preferred channels reduces salt levels, and hence can be beneficial unless the outflows become blocked. The realised outcomes depend on the changes relative to the natural balance and can only be predicted given reliable information on the characteristics of the system.

General Evidence

The process identified here differs from that in the Australian Dryland Salinity Assessment 2000 in:

- Addressing structural changes in the soil associated with land use.
- Focussing on the water balance of the surface soil rather than invoking controls by underlying water tables.

The addressing of soil structural change should not require justification. Soil structure is affected by land use, and soil structure largely determines the patterns of sub-surface flows of water that are crucial in determining the occurrence of dryland salinity.

Most models used to address dryland salinity dryland salinity do not consider changes to soil structure. Moreover, some models that do incorporate soil permeability are insensitive to changes in this variable, as with TOPOG. The incorporation of other assumptions, such as subsurface flows directly reflecting surface topography, can mean that the results bear little relationship to reality (Tunstall et al., 1995).

The focus on surficial water balance arises because this determines the patterns of movement of water and salt, and dryland agriculture only directly impacts this surface layer. Scenarios that focus on other parts of the system, or which do not correctly address system function in the surface metre, are unlikely to produce valid conclusions.

The process described is physically sound and accords with all observations. In particular:

- It does not depend on the existence of constraints or structures that are not general, such as ground water systems.
- It accounts for waterlogging as well as salinity, where increased waterlogging is an adverse outcome of agricultural land use.
- The time scale for the structural changes to have effect accords with observations of the long delay between the implementation of agricultural land use and the occurrence of adverse salinity outcomes in local as well as regional systems.

- It accounts for the ability to remediate salt scalds through local treatments such as applying gypsum, planting grass, and excluding livestock.
- It accounts for the ability to remediate areas without planting trees.
- It accounts for situations where surface expressions of salinity progressively develop, and where salinity expressions fluctuate with climatic variations.

Addendum

The following examples illustrate the above scenario and were accessed following completion of the paper. The results in the examples run contrary to the rising groundwater model and its associated assumption that dryland salinity is due to increased percolation of water into the subsoil due largely to the clearing of trees. The examples are sequenced in order of access.

Water Balance, Burnett Region, Queensland

Source: Bell et al. (2001)

This paper reports field observations and model results on changes to the water balance of degraded and improved pasture systems on Ferrasols in the Burnett region. The loss of water through percolation and surface runoff accounted for 20% of the rainfall (150mm) in both situations but most (110mm) occurred as surface runoff in the degraded system and effectively all occurred as percolation in the improved system. The soil in the improved pasture had higher organic matter, lower compaction, and improved structure compared to the degraded system.

The main result is that improvements in soil structure associated with an increase in organic matter decreased surface runoff but increased percolation. The result runs contrary to the assumption made in the rising groundwater model for dryland salinity that suggests that agricultural impacts increase percolation. Despite this the authors still conclude that *"Unless this deep drainage is countered, the resultant groundwater accessions will raise water tables and increase the incidence of dryland salinity*." As the functioning of the improved system is much more similar to the original intact (natural) system than the degraded one, and as dryland salinity did not occur in the intact system, this conclusion is illogical.

Ameolieration of Salinity, Lockyer Valley, Queensland

Source:ABC news online, Transcript of AM broadcast of 9 April 2002-04-10

The transcript reports an interview with Professor Victor Rudolph of Queensland University relating to the use of waste from coal power generation to remediate salinity. Application of gypsum was identified as successfully remediating expanding salinity near Gatton. This response is incompatible with the rising groundwater model as there is no substantive change to water use, and application of gypsum serves to increase rather than decrease percolation of water through the soil.

The gypsum displaces sodium on the clay and tends to flocculate the clay and increase its permeability. The increased drainage (percolation) reduces adverse salinity.

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