DRYLAND SALINITY IMPLICATIONS OF INTERACTIONS BETWEEN CLAY, ORGANIC MATTER, SALT AND WATER IN SOILS

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Introduction

The rising groundwater model was officially identified as being the general model for dryland as well as irrigated salinity and therefore deemed applicable to all occurrences of adverse salinity. Dissent to this view was widespread in coming from farmers, agency field personnel, and independent scientists. Application of the rising groundwater model simplistically addresses the soil and plant water balance where this is the prime determinant of the flows of water and salt. Moreover, it is this surficial water balance that is directly impacted by land use. Groundwater systems are not directly impacted by land use and hence cannot be causal in dryland salinity.

The rising groundwater model has the cause of dryland salinity being increased recharge of groundwater systems due to reduced water use associated with clearing trees. An alternate view was presented by Jones[1] and Tunstall[2] who independently concluded that dryland salinity is primarily caused by soil structural decline arising mainly from a loss of organic matter. The difference in views arises from difference between application of hydro-geologic and ecological approaches. The ecological approach takes account of how the systems naturally functioned rather than attempting to predict how they previously functioned by limited observations on degraded systems.

The inapplicability of the rising groundwater model as being general was acknowledged in the report from a Commonwealth Government review of dryland salinity[3]. Tunstall[4] discusses the basic physical mechanisms underlying the development of dryland salinity and, while not fully understood, they are reasonably straight forward. However, there can be many forms of expression of dryland salinity depending on geomorphic constraints.

The general inapplicability of the rising groundwater model and occurrence of different forms of dryland salinity were also acknowledged in the Land and Water Australia submission to the Government salinity inquiry where the main finding from the National Dryland Salinity Program was identified as being that the problem was more complex than they had expected. The assumed general model was not general and the lack of alternative models resulted in piecemeal addressing of new situations as they were discovered.

The research focus on the generally inapplicable rising groundwater model has provided little if any benefit over the past 30 years. Predictions include comments that the problem will

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[1] Jones, C. E. (2000). The great Australian salinity debate Part 1:Controlling the salinisation processes. Holistic Management Aust. Quarterly Newsletter, July 2000.
Jones, C. E. (2000). The great Australian salinity debate Part 2: why the recharge:discharge model is fundamentally flawed. Stipa Native Grasses Newsletter 14, 6-11
Jones, C. E. (2001). The great Australian salinity debate Part 3: Soil organic matter: past lessons for future learning. Stipa Native Grasses Newsletter 15, 4-9

[2] Tunstall, B. R. (2001) Scenario for Dryland Salinity. Available on http://www.eric.com.au

[3] Inquiry into salinity conducted by the House of Representatives Standing Committee on Science and Innovation. Submissions and report available on http://www.aph.gov.au/house/committee/scin/salinity/

[4] Tunstall, B. R. (2004) What Model for Dryland Salinity?. Available on Available on http://www.eric.com.au

become worse before it gets better, and that it will take over 1,000 years to resolve. Some scientists have resigned themselves to extensive ongoing land degradation by admitting they cannot solve the problems in their suggestion that people should be removed from the land.

The simplistic single factor approach and defeatist attitude of some scientists contrasts with the holistic and determined efforts of some landholders. The recently publicised Natural Sequence Farming (NSF) remediated salinity by increasing water accessions into the soil. The earlier work by Whittington (Paulin[5]) charts a 20 year period of land degradation followed by remediation over 15 years. In the 1950s Whittington demonstrated that the adverse salinity on his Western Australian landholding could not have arisen through rising groundwater as piezometers in subsoils were dry where water was seeping from the soil surface.

The commonality of the NSF and Whittington Interceptor Banks (WIB) is the increased plant production and reduced adverse salinity achieved by increasing soil organic matter through making maximum use of available water. The principles are largely the same as with the Keyline approach to landscape management (Yeomans 1958, 1978, 2002)[6]. The key point with such systems is the demonstration that adverse salinity can be reversed by improving the soil organic matter where the ability to reverse an effect is a reliable test of cause.

This paper addresses the mechanisms for the effect of organic matter on soil salinity. It details the interactions between clay, organic matter, salt and water in soils relating to the role of soil organic matter in dryland salinity

Clay – Salt – Water

The three factors are jointly evaluated as they invariably co-occur in soils. No two can occur without the other.

Soils start as mixtures of different mineral materials of which clay is the smallest sized particle. Clay soils are referred to as being fine textured. The other mineral components can be variously categorised but are most simply grouped into particle size classes of represented by loam, sand and gravel. However, the colloidal clay fraction is the most important mineral fraction determining the soil properties relevant to their hydrology and interaction with plants. The small size of clay particles of less than 2 microns, and their physical structure result in a very large surface area relative to volume where the interactions between soil, salt and water relate to surfaces.

Structure

The importance of clays to the function of soils arises from their ability to adsorb ions and water. However, clays represent a highly weathered product and their construction does not involve any of the macro nutrients needed for plant growth. Their function lies in adsorption and hence the retention and exchange of water and nutrients derived from other sources.

Clays are made of two or more mineral-oxide layers stacked as parallel units of silica and alumina sheets. Silica form tetrahedral sheets and alumina octahedral sheets. The particle

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[5] Paulin, S. (2002). Why salt? Harry Whittington, OAM and WISALTS: Community Science in Action. Indian Ocean Books, Perth. 63 pp.

[6] Yeomans, P. A. (1958) The challenge of the landscape: The development and practice of Keyline. Keyline, Sydney, NSW.

Yeomans, P. A. (1978). Water for every farm using the Keyline plan. Murray Books, Ultimo, NSW.

Yeomans, K. (2002). Water for every farm: Yeomans Keyline plan (2nd ed.) Keyline designs, Southport, Qld.

stacks may be neutrally charged by having an equal number of negative and positive charges or have abundant negative charges.

Changes to layers and substitutions to elements in the layers produce different clays. Substituting a divalent cation (Mg^{++} or Fe^{++}) for a trivalent element (Al^{+++}) will create a negative charge that can distribute itself principally over 10 surface oxygen atoms of four silica tetrahedra. Substituting aluminum (Al^{+++} for silicon (Si^{++++}) in the tetrahedral sheet will create a negative charge that is distributed primarily over three surface oxygen atoms of one tetrahedron. This negative charge is compensated for by the adsorption of a cation on the interior or exterior of the stack: clays form complexes with cations and dipolar molecules such as water.

The charges on clay surfaces are identified as either permanent or induced, noting that such bonds are transient: descriptions relate to a dynamic equilibrium. Permanent charges are produced by isomorphic substitutions and are negative. Induced charges, which depend upon pH and are positive, mainly originated by breaking bonds at the ends of the clay platelets. The Cation Exchange Capacity (CEC) quantifies the ability of clays to adsorb positively charged ions (Table 1).

Table 1. Characteristic cation exchange capacities of soils and soil components (meq/100g).

Material	CEC		Soil Texture	CEC
Kaolinite	3-15		Sand	1-5
Illite	15-40		Fine Sandy Loam	5-10
Montmorillonite	80-100		Loam	5-15
			Clay Loam	15-30
Organic Matter	200-400		Clay	>30

Clays differ markedly in their ability to adsorb ions and water. Platelets of illite-vermiculite clays are generally bonded by hydrogen and kaolinite clays by potassium and these bonds limit their adsorption of cations. Smectites and other reactive clays (montmorrillonites, bentonites and zeolites) have various cations on the surfaces of the clay platelets which have a strong affinity for polar solvents. Under humid conditions the interlayer cations and the internal clay surfaces hydrate causing the clay to swell in a series of steps. For montmorillonite this occurs as one-, two- and three layer hydrates.

Salts

The salts are mainly ionised and so must be addressed by way of their constituent ions. For example, NaCl dissociates into Na^{+} and Cl^{-}.

The anion exchange capacity (AEC) increases as soil pH decreases but the AEC of agricultural soils is generally small compared to their CEC. The mineral anions such as nitrate ($NO_3^{-)}$ and chloride (Cl^{-}) that are repelled by the negatively charged clays are therefore mainly in the bulk soil solution and are thereby susceptible to leaching.

Exchangeable cations on clays can become available to plants as plant roots also possess cation exchange capacity. Hydrogen ions from root hairs and microorganisms may replace cations on the soil. The released cations can then be adsorbed on the surfaces of roots and soil organisms. Such plant uptake is affected by the composition of cations as, for example, uptake of K being limited by high levels of Ca and high levels of K limiting uptake of Mg.

The concentration of cations is highest at the surface of the clay particle and decreases moving away, being lowest in the bulk soil solution. Cations such as Ca^2, Mg^2, K and Na are basic while Al^3 and H are acidic. In highly acidic soils Al^3 and H dominate on the clay surfaces while in neutral to slightly alkaline soils Ca^2 and Mg^2 dominate. The base saturation is a measure of the proportion of basic cations occupying exchange sites and is inversely related to soil acidity. High base saturation is preferred for agricultural soils as the availability to plants of nutrient cations such as Ca, Mg, and K increases with increasing base saturation.

The strength of the attractive force between a cation and the clay surface depends on the charge of the cation, the charge density of the surface and how close the cation can get to the surface. The proportion of different adsorbed cations depends on the strength of this force. When the cations are present in equivalent amounts the order of strength of adsorption is $Al^3 > Ca^2 > Mg^2 > K = NH_4 > Na$.

The relative concentration of the cations in the soil solution also determines the degree of adsorption. Very acid soils will have high concentrations of H and Al^3. In neutral to moderately alkaline soils, Ca^2 and Mg^2 dominate. Poorly drained arid soils preferentially adsorb Na. Base saturation is usually close to 100% in arid region soils.

The relative concentrations of cations impact on the behavior of clays. For example, dispersion occurs in soils with high proportions of sodium because sodium has a single charge and a large hydrated ionic radius. The clay platelets are repelled rather than being attracted. In calcium saturated systems the attractive forces are greater than repulsive forces because calcium has a small hydrated ionic radius and the clay particles flocculate.

The sodium absorption ratio (SAR) provides an indication of the tendency of salinity to disperse clay soils. However, while sodium promotes dispersion and calcium promotes flocculation, clays flocculate at high salinity levels regardless of the salt composition. An SAR less than 12 to14 is generally considered desirable but soils with very low levels of salts can disperse at an SAR around 3. The SAR of irrigation water should be below 6.

Generalised relationships have been developed between salinity levels and SAR on soil dispersion but these are only indicative because the effect depends on the composition of the clay which is seldom known. Moreover, aggregation is promoted much more by calcium than magnesium thus the significance of the SAR depends on the relative composition of cations additional to sodium. Measures of salinity and dispersibility are of greater value, practically and theoretically, than measures of salinity and SAR. Moreover, dispersibility is easier to measure than the SAR. The discrimination between soil salinity and sodicity would best focus on the important outcome which is dispersibility.

Characteristics of dispersed clays include:

- Lack of structural strength.
- Very low conductivity for water.
- Reduced water holding capacity at high water potentials.
- Very low permeability for air. They are generally anaerobic.
- High susceptibility to erosion.

Flocculation arises where the clay platelets are ionically bound in a parallel fashion and the particles aggregate to form a stable structure. This aggregation creates voids (gaps) between the aggregates. Characteristics of aggregated clays include:

- Good structural strength.
- High conductivity for water.
- High water holding capacity.
- High permeability to air.
- Low susceptibility to erosion.

Measurement of CEC

The CEC of a soil is not fixed or static and the estimate varies depending on the measurement method. The basic methods for determining CEC involve displacing the cations and measuring either the cations displaced or the adsorption of an introduced cation. The CEC of most soils increases with an increase in soil pH and is either measured at the field or a set pH. The increase in CEC from pH 4.0 to 6.5 is around 50% while it generally doubles from pH 4.0 to 8.0.

Adsorption a specific cation that is rare in soils provides the only direct measure of CEC but the measure is not absolute as the value depends on the size of the molecule used. Moreover, the measurement is time consuming and the standard method produces toxic materials. Measurement of displaced cations is a simpler procedure that links with other measures of soil properties and is therefore most commonly used.

Routine CEC estimates are usually based on the quantities of Ca^2, Mg^2, and K extracted by normal soil test solutions. In acid soils of pH <5.5 significant quantities of exchangeable Al_3 cause an underestimate of the CEC. With alkaline or salty soils some of the Ca^2 and Na measured is not attached to exchange sites thereby producing an overestimate for CEC. The error can be 15 meq/100g for severely salt affected soils.

Soil Water

As the solvent, water provides the medium for the movement of ions. Its bi-polar nature is a key structural characteristic whereby the positive and negative charges at opposite ends of the molecule promote binding with a wide range of elements and compounds. The bonds normally ignored in studies are between the water molecules. Water molecules tend to form clusters and the greater the clustering the less the interaction with other molecules. Some magnetic and/or mechanical water conditioners reduce the size of the clusters of water molecules and so increase its ability to interact with other molecules. Removing trace amounts of gas from water has been shown to increase the electrical conductivity of water by a factor of 20 (Kondrachuk et al. 1994[7]., Pashley et al. 2004[8]) where this is associated with a change to the arrangement of bonds between water molecules.

The characteristics of water bonds in the clay interlayers are generally given as a shell around cations by chemists and as layers between cations bonded to the clay surface by physicists. These are not necessarily mutually exclusive as the concentration of cations decreases away from the charged surface. Neutron diffraction studies of hydrated montmorillonite indicate that the interlayer water gives a liquid-like contribution to the diffraction pattern indicative of

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[7] A. V. Kondrachuk, V. V. Krasnoholovets, A. I. Ovcharenko and E. D. Chesnokov, Determination of the water structuring by the pulsed NMR method, *Khim. Fiz.* **12** (1993) 1006-1010; translated in *Sov. Jnl. Chem. Phys.* **12** (1994) 1485-1492.

[8] Pashley, R. Desalination Works Better Without Gas J. Phys. Chem. B.

hydrogen bonding (Powell et al.[9]). However, it is not certain whether the water in interlayers between platelets is structurally the same as in the bulk solution and there is evidence to indicate that it isn't.

Liquid water has been shown to have two structural forms that represent high and low density states. The existence of these states confers many apparently anomalous properties to water and Wiggins[10] examines the implications of these for life. While important, the structure of water is not further considered because of the limited information specifically relating to soils. It is raised because it provides a means of reducing soil salinity using magnetic and/or mechanical water conditioners and because of assumptions made when calculating the osmotic effect of dissolved salts (Tunstall, 2005)[11].

Water is inevitably lost as plants gain the CO_2 needed for the production of carbohydrates and this is obtained from the soil. Soil water affects plants through its amount and availability as well as by the way it affects the availability of nutrients.

The beneficial aspects of soil water relate to its dissolution of solutes and transport of ions. The potential detrimental or limiting aspects of soil water include:

- Limited amount
- Limited availability
- Reduced aeration

The effect of storage on the amount of water is addressed here but not the effect of climate. It is assumed that rainfall is intermittent and limiting such that the soil operates as a buffer store in providing water during periods without rain. Losses of rainfall to productive plant use include evaporation of water intercepted on foliage, evaporation from the soil surface, surface runoff, and drainage and leakage from the bottom. The drainage and leakage combine to form percolation which recharges groundwater systems.

The separation of drainage from leakage is somewhat arbitrary but the differentiation is useful when addressing changes in hydrology with changes to soils. The hydraulic conductivity decreases exponentially as the soil dries and most flow occurs in saturated soils. Water flow in unsaturated soils is much lower than when saturated. The net effect of patterns of soil dryness on drainage through a soil profile depends on the patterns of water extraction by vegetation as well as soil properties but in homogeneous soils there is little percolation until the soil profile becomes saturated as the forces holding water in dry soils are much greater than the gravitational force that produces drainage. The soil tends to operate like an inverted bucket filling from the top down, effectively overflowing when it fills to the rooting depth. This overflow from the bottom is referred to here as drainage.

In functional soils structural features such as cracks and old root channels provide preferred pathways for flow. Appreciable water can drain from soil profiles even though the profile is

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[9] D.H. Powell, D. H., Fischer H.E., Skipper N.T. Probing the water interactions in clay. http://www.ill.fr/AR-98/page98/25liqui.htm

[10] P Wiggins (2004) Life depends upon two kinds of water. Under Extras: contributed papers on http://www.lsbu.ac.uk/water/index.html

[11] Tunstall, B. R. (2005) Interrelationships Between Salt Content, Water Content and Water Potential in an Expansive Clay Soil. On http://www.eric.com.au

unsaturated because of localised saturated flow. This flow is here termed leakage. Cracks and old root channels have much greater capacity to transport water than a homogeneous soil with small, poorly connected voids.

The forces that hold water in the soil and limit drainage also limit its uptake by plants. The force is termed water potential and is quantified by way of the free energy of the soil solution relative to pure water. The main components are matric, osmotic, pressure and gravitational. Traditionally the pressure potential has been attributed solely to an elevation difference in confined and semi-confined aquifers but recent knowledge identifies the likely existence of very local pressure gradients. These are associated with differences in osmotic potential deriving from differential affinities of ions for different structural phases of the water.

The matric and osmotic potentials are invariably negative (tensions) as the surface forces/ ionic attractions reduce the availability of water. The soil water potential is given by the sum of the matric, osmotic and pressure components. The total soil water potential additionally includes the gravitational component.

Partitioning into osmotic and matric components addresses salts in solution being potentially mobile. The matric potential relates to the soil structure and hence, compared with salts, is locationally static. The matric force derives from the interaction between water and the soil surfaces with water in close proximity to a surface being more tightly bound than when distant. While the matric force can variously be partitioned into ionic and capillary the basis for the forces are the same in relating to the chemical affinity between water and surrounding surfaces. This is reflected in the relationship between soil water content and water potential being a continuous function.

The osmotic reduction in water availability is taken to be additional to the matric potential. The partial free energies are additive hence the water potential is the sum of the matric and osmotic potentials. For most methods used to quantify these soil properties this relationship arises by definition and it can be difficult to determine whether this conclusion is applicable.

While the situation is uncertain there is sufficient evidence to justify the conclusion that, at water potentials and salt concentrations of most consequence to plants, all soil water tends to be equally available to dissolve solutes and that the matric and osmotic components are separate and additive. The ions on clay surfaces and ions in the bulk soil solution therefore contribute similarly to the osmotic potential. However, in dry soils the osmotic potential is considerably greater than predicted with this assumption as the water is not equally available to all ions. The magnitude of this effect increases with increasing concentration of ions.

This conclusion is significant when evaluating the osmotic effect of salt added to soils. Blackmore (1976[12]) showed that clay can reduce the salinity of percolating water and this has apparently led some to consider that the adsorption of ions increases the osmotic potential of the soil solution. From the physical evidence this does not apply. Adsorption of ions by clays increases soil salinity by increasing the amount of salt in the soil and decreases (makes more negative) the osmotic potential.

The relationship between water content and water potential is logarithmic with most water being released at high water potentials (readily available water) but some is retained at low water potentials (dry soils). For non-clay soils the relationship can be reasonably predicted from the particle size distribution as this identifies the distribution of pore sizes. However, as indicated by the CEC, the ability of clays to hold water varies with the type of clay mineral so

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[12] Blackmore, A.V. (1976). Salt sieving within clay soil aggregates. Aust. J. Soil. Res. 14, 149-58

the prediction of the water release function from soil structure has low reliability for many soils. This is compounded by the occurrence of organic matter.

Clay increases the amount of water a soil can store but decreases its availability. Less water is freely available than in sands but there is a more continuous supply as the soil becomes dry. However, the effect depends strongly on the level of aggregation. Dispersed clays have no voids so little water is freely available. Well aggregated clays with extensive voids store considerable water that is readily available to plants.

The hydraulic or drainage properties of soils reflect their water release characteristics but differences are of much greater magnitude. Soils with high proportions of readily available water have high hydraulic conductivities. This is accentuated with swelling clays as the cracks that develop in the dry rapidly conduct water from rainfall. The changes in drainage encompass several orders of magnitude. The aggregation of clay reduces surface runoff of water but increases leakage.

Aeration is similarly positively related to the level of readily available water and hence drainage. Good aeration depends on some pores being sufficiently large that they cannot hold water against the force of gravity. A desirable situation is for a soil to contain 50% air.

Clay – Organic Matter

Organic Matter

Soil organic matter is referred to here in a restricted definition of organic material in soils arising from the breakdown and synthesis of organic material formed directly or indirectly through photosynthesis. It therefore does not include surface litter or live plant roots as litter is not in the soil and plant roots have never been broken down. Organic matter is around 1.724 times the amount of organic carbon

Humus is the major soil organic matter component, making up 65% to 75% of the total as breakdown of humus is slow under natural soil conditions. Non-humic organic materials include carbohydrates, fats, waxes, alkanes, peptides, amino acids, proteins, lipids, and organic acids. Most small molecules of non-humic substances are rapidly degraded by soil microorganisms and are important in recycling nutrients to plants. However, the protein glomalin, which is estimated to comprise around 30% of the soil organic matter, is identified as being resistant to breakdown.

This paper addresses the natural development of soil organic matter but does not address the recycling of nutrients through non-humic organic matter. Also, the artificial addition of organic matter is not addressed other than to note that anaerobic conditions can result in the development of methane (CH_4) which is toxic to plants. The outcome depends on the amount and nature of the organic matter and the soil conditions.

Humus comprises high molecular weight compounds that together form brown to black hydrophilic, molecularly flexible, stable organic complexes. Humus is primarily composed of carbon, oxygen, hydrogen, nitrogen, and sulfur in complex carbon chains but humic substances have a wide variety of components. Its provision of nutrients through breakdown of its basic components is limited and its key role in soils is as an organic colloid. Humus binds cations and water similarly to clays but on a dry weight basis has much greater capacity (Table 1). It also aggregates and binds the mineral soil fractions of all sizes including clays.

Humic substances can be subdivided into three main fractions of humin, and humic and fulvic acids. These sub-divisions are based on the solubility of each fraction in water depending on pH. Humins are insoluble in water, fulvic acids always soluble, while humic acids are only soluble under alkaline conditions and precipitate at low pH.

Humins have very high molecular weights, around 10,000 times that of carbohydrates, and are most resistant to breakdown. Humins improve the soils water holding capacity, improve soil structure, maintain soil stability, provide cation exchange, and generally improve soil fertility.

Humic acids are considerably smaller with molecular weights in the range 10,000 to 1,000,000 and are considered to be polymerization products of fulvic acids and other decay products. They comprise a mixture of weak aliphatic (carbon chains, 65%) and aromatic (carbon rings, 35%) compounds. Three dimensionally they are considered to be flexible linear polymers that exist as random coils with cross-linked bonds. Humic acids readily bind clay minerals to form stable organic-clay complexes. They adsorb cations and have a very high CEC.

Fulvic acids have molecular weights around 275 to 2,100 and their composition and shape is variable. They are considered to be decay products of higher plants and microbial residue. Fulvic acids have twice the oxygen content of humic acids and have many carboxyl (-COOH) and hydroxyl (-COH) groups making them chemically reactive. Their CEC is more than double that of humic acids. Their relatively small size allows fulvic acid molecules to readily enter plant surfaces such as leaves and roots carrying minerals with them.

Humates are the mineral salts of humic and fulvic acids and comprise a large diversity of complex molecules. Humates are formed by dissociation of the hydrogen ion of the carboxyl (-COOH) and hydroxyl (-OH) groups on the outside of the polymers. Two of these anions can bind to positive metal cations, such as iron (Fe++) and calcium (Ca++). The composition of humic substance is highly variable and varies with the mineralogy of the soil.

The general process of humification is given as breakdown and transformation of organic plant material by bacteria and fungi into humic and fulvic acids and a variety of other organic substances that accumulate on the surface of soil particles. These soil-organic matter complexes are then further cemented together into micro-aggregates by more persistent organic matter. The production of glomalin is associated with humification as the protein is produced by arbuscular fungi that form symbiotic relationships with plant roots. There are feedback processes with soil structure controlling microbial activity by controlling the physical environment.

Porosity strongly influences the rate of breakdown by controlling aeration and access by micro-organisms. Bacteria are said to require pores at least 3 times their own diameter which excludes them from many parts of clays, particularly the interlayers between platelets. The physical separation between microorganisms and organic molecules partly accounts for the tendency of clay soils to accumulate organic matter. The half life of humic compounds ranges from hundreds to over a thousand years. The life span of glomalin is given as ranging from 7 to 42 years.

Organic molecules may occur between clay micro-aggregates and within interlayers of swelling clays such as montmorillonite. High resolution transmission electron micrographs show organic molecules within ~1.0 µm diameter pores between clay crystals. Such an occurrence would protect the organic mater against microbial attack. It would also increase the structural stability of the clay in the presence of sodium ions.

Organic substances are generally identified as coating mineral particles such as clay, potentially protecting the coated particles from weathering. However, there are also observations of clays forming protective layers around organic matter. In both cases there are strong clay-organic matter interactions.

Prime Controls on Soil Organic Matter Accumulation

- The threshold soil temperature for organic matter accumulation is around 25 C. The soil organic matter increases 2-3 times for each 10 C decrease in mean annual temperature.
- Wet soils tend to accumulate organic matter faster than comparable dry soils due to reduced aeration Arid soils generally have relatively low organic matter content because of high rates of decomposition as well as low inputs.
- Organic matter tends to be higher under grassland than forests. Roots of grasses provide higher levels of input than from trees where organic matter from roots is more protected than surface litter. Moreover, grasses preferentially occur on finer textured soils.
- Fine textured soils (clays) tend to accumulate organic matter more than coarse textured soils due to deceased aeration and protection of the organic matter.

High levels of clay help protect organic matter from breakdown and so promote the accumulation of organic matter. However, the relationship between clay type and content and organic matter accumulation is difficult to accurately determine because of variations in the forms of clay and organic matter in soils. There is evidence that clay type and the associated cations influence organic matter stabilisation while organic matter is important in the formation and stabilisation of soil structure. Moreover, clay content is usually positively correlated with increased organic matter production and the promotion of grasses which increase the input of organic matter into the soil.

Organic matter generally accumulates under cold, anaerobic conditions such as seasonally waterlogged clays and wetlands. This also arises in warmer areas with rice paddies. The organic content of surface soil is almost invariably greater than the subsoil due to patterns of input.

Impacts of Organic Matter on Soils

Soil Aggregates

Organic material coats particles of silt and clay and helps bind them into aggregates, but it improves aggregate stability more than aggregate formation. This stabilisation mainly arises through the by-products of organic matter decomposition such as glomalin.

While this stabilising effect is generally accepted there are results indicating that organic matter increases the dispersibility of clay soils. It appears that with some results at least the effect is an artifact of the sampling procedure with the evaluation being based on a comparison of surface and subsoils. Variations in other soil properties can produce such a result.

Generally, addition of organics decreases the amount of small aggregates (0.25 mm diameter) and increases the larger aggregates (1-2, and 4 mm diameter). The mean diameter of water stable aggregates tends to increase exponentially in proportion to the amount of organic material applied. Aggregate stability generally increases logarithmically as organic matter increases, while the percentage of water stable aggregates and the soil organic carbon content are linearly related.

Cation Exchange Capacity

Organic matter has higher CEC than clays and contributes substantially to the CEC of surface soils. From 7 to 20 % of the CEC of many surface soils is due to organic matter. The adsorption of water by organic colloids produces a high specific surface area. However, the CEC of soil organic matter is strongly pH-dependent and buffered over a wide range of hydrogen ion concentrations. As pH increases the hydrogen ions can be replaced by other cations and around neutral pH the other cations can exchange with each other.

Polyvalent cations such as Ca^2 help stabilise both organic and inorganic colloids favoring a stable flocculated condition. Polyvalent cations enhance structural stability by serving as bridges between negatively charged clays and organic colloids. Ca^2 and Mg^2 are the major bridging cations in neutral and alkaline soils and Fe^3 and Al^3 serve a similar role in acid soils.

Bulk Density

Organic matter generally decreases the bulk density of soil by comprising less dense material (1/4) and/or by increasing aggregation. At reasonably low levels of organic matter the effect on aggregation is most important and is effectively independent of soil texture.

Soil Moisture

Humic and fulvic acids are hydrophilic and organic matter can hold up to 20 times its weight in water. However, soil organic matter has a variable effect on the amount of soil water available to plants. It is generally positive but whether the effect is considered significant depends on other soil properties, notably texture, and the means used to determine its effect.

Some consider organic matter only increases available water in soils of medium to low clay content. Although the water contents of clays at the wilting point and field capacity were altered by addition of organic matter there were no significant differences in plant available water. In some situations this reflects the impact of recent additions of organic matter which did not produced the structural development of soil that arises with natural accumulations.

Some equations predicting the relationship between soil water and physical and chemical properties have organic matter as being insignificant where this reflects the mode of derivation of the relationships. It is an artifact of the method. Some embody the effect of organic matter with clay by using CEC in the predictive relationships. The most explicit equations are given by Rawls et al. (1982) as they provide relationships for discrete water potentials rather than attempting to predict the entire water release curve with one regression. The results given below indicate that organic matter has around 14 times the effect of clay at a water potential of 0.01 MPa, 7 times at 0.06 MPa, and 3 times at 1.5 MPa. Organic matter increases the total water storage but also increases the level of water available to plants by increasing the water content at field capacity or drained upper limit more than the nominal wilting point.

Rawls et al. (1982)

$$\theta_{0.01} = 0.4118+(-.0030*\text{sand})+(0.0023*\text{clay})+(0.0317*\text{Organic Matter})$$

$$\theta_{0.06} = 0.2065+(-.0016*\text{sand})+(0.004*\text{clay})+(0.0275*\text{Organic Matter})$$

$$\theta_{1.5} = 0.026+(0.005*\text{clay})+(0.0158*\text{Organic Matter})$$

Water content θ in m^3/m^3. Textures and organic matter in proportions (g/g). Water potentials for each θ in MPa.

Some suggest that organic matter can increase the water holding capacity of soils by 400%. This is only physically possible for coarse sands but then only for available and not total water. Even assuming that the organic matter does not increase the water content at the nominal wilting point of 1.5 MPa (it does) there is insufficient soil volume available to be filled by water to achieve a 400% increase with all other soil textures. Moreover, it is unrealistic for sands because the proportion that will be occupied by air prevents the achievement of a 400% increase.

The structural changes in soils produced by humus reduce the bulk density of the soil material and therefore increase the soil depth. This produces an increase in soil water storage additional to changes in the water holding characteristics of the soil material. The combined effect of the change in soil depth and the water holding capacity of the material may therefore achieve the magic 400% change. However, this only applies to the A1 horizon.

Soils develop distinct profiles with the differentiation arising from patterns of water extraction and provision of organic matter by plants. The A1 horizon is identified by the accumulation of organic matter and the A2 by leaching. While organic matter can be distributed throughout the A and B horizons it mainly accumulates in the A1. Large increases in water holding capacity therefore only apply to the A1 horizon and not to the profile generally.

The greatest potential to increase the water storage of soils for plants can arise through increasing the effective rooting depth. The potential benefits vary with the water holding capacity of the soil and the characteristics of rainfall and plant water use but it promotes plant growth and survival during extended periods without rain. The significance of increasing the plant rooting depth is greater than the realised increase in the soil water storage in the range of water potentials where water is available to plants.

Some implications of increasing the plant rooting depth are poorly understood. Roots are typically subject to a range of water potentials due to spatial patterns of soil water content and salinity. At zero transpiration the water potential of plants should be close to that of the most freely available water but divided root experiment show it is roughly mid way between water at different potentials. Moreover, alternating irrigation on different sides of grape vines can trick plants into behaving as if water availability is restricted. Water use by plants is influenced by the spatial as well as temporal patterns of soil water availability.

Infiltration

Organic matter has a strong, positive effect on infiltration of water into soils due mainly to a decrease in bulk density and improvements in aggregation and structure. The hydrophilic nature of organic matter increases adsorption. This promotion can be counteracted in some soils due to the production of hydrophobic compounds by fungi. The water repellency only occurs when the soil is dry.

Water Movement

Hydraulic conductivity usually decreases exponentially as the soil water content decreases from a saturated to a near-dry state. When water content changes with soil depth or with time the hydraulic conductivity correspondingly changes. Moreover, the hydraulic conductivity is spatially highly variable. The realised patterns of water flow in soils can be complex.

In coarser textured soils organic matter generally increases the saturated hydraulic conductivity and decreases the unsaturated hydraulic conductivity. The higher saturated conductivity increases infiltration and reduces surface runoff. The lower unsaturated hydraulic conductivity potentially reduces water losses through direct evaporation from the soil surface.

Improved aggregation of clays increases the saturated hydraulic conductivity. While this benefits wetting of the surface soil the changes to the subsoil are less certain. The main issue relates to assumptions concerning the soil operating as a homogeneous porous medium that is vertically stratified but horizontally uniform.

Peck (1973[13]) showed that the salinity of water percolating through soils is not in equilibrium with the bulk soil salinity. This disequilibrium arises because water preferentially flows along pathways of least resistance such as cracks and old root channels. The effect of soluble organic fractions in subsoils is therefore realised locally in such structures rather than uniformly through the soil. The effect of organic matter on subsoils cannot be predicted from its average concentration.

Bell et al.[14] identified that the improvement in soil structure associated with an increase in plant growth and soil organic matter did not alter water use by pasture but did change the nature of the water loss. Water was lost by surface runoff from the degraded soil and by percolation from the soil with improved structure. General observations following the introduction of cellular grazing identify that dams become dry, reflecting the reduced surface run off, but that springs can develop. The latter reflects increased percolation of water through the soil. The same pattern of water loss was identified by Whittington.

The improved productivity of grasses without an increase in water use represents an increase in water use efficiency by plants. The apparent inability of plants to use the additional water entering the soil likely arises through changes to the soil structure rather than atmospheric limits to evaporation. Improvements to soil structure likely increase the leakage where this increases the frequency as well as amount of percolation.

In many soils land use impacts such as tree clearing have decreased rather than increased the percolation of water through soils. The general situation is evidenced by patterns of stream flow in SE Australia. These were once strongly winter dominant but appreciable flows now arise in summer and winter peaks have declined.

In SE Australia rainfall is reasonably uniform across the year but the potential evaporation is strongly summer dominant. An excess of rainfall over evaporation only occurs over winter where patterns of stream recharge through percolation reflect the balance between rainfall and evaporation. The prior winter flow pattern identifies that stream flows arose through percolation and surface run off when soils became saturated.

Patterns of stream recharge through surface runoff mainly reflect patterns of rainfall. The occurrence of appreciable accessions over summer and reduction in winter flows identifies that land use has increased surface runoff and reduced percolation. These changes accord with what would be expected from the degradation of soil structure associated largely with the decline in organic matter.

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[13] Peck, A. J. (1973). Chloride balance of some farmed and forested catchments in southwestern Australia. Water Resour. Res. 9: 648,57

[14] Bell, M. J., Bridge, B. J., Harch, G. R., Want, P. S., Orange, D. N. and Connolly, R.D. (2001) Soil structure affects water balance of Ferrosol cropping systems. Proceedings of a GRDC conference, Kingaroy (www.regional.org.au/au/asa/2001/3/b/bell.htm)

Oxidation-Reduction Potential (Eh or pe[15])

The increased aeration associated with aggregation increases the level of oxidation but the addition of large amounts of organic material can temporarily reduce the pe. Organic materials act as electron donors in microbial respiration, so C-rich waste is likely to make soils more electron-rich and reducing.

pH Buffering

The addition of humic substances helps neutralise their pH with both acidic and alkaline soils being neutralised. This neutralisation increases the availability of many trace elements.

Humic substances also release carbon dioxide from calcium carbonates. The CO_2 may be taken up by plants or form carbonic acids which promote the release plant nutrients from soil minerals. In soils containing lime the release of CO2 by grass roots has been shown to promote the leaching of sodium by increasing the dissolution of calcium.

Salinity

Soils with appreciable clay content are of most consequence for salinity due to the ability of clays to adsorb ions and the effect of sodium in dispersing clay.

Organic matter can have a pronounced effect on soil salinity by promoting leaching by increasing the percolation of water through the soil. This leaching can be reasonably spatially uniform in the surface soil but can be spatially localised in subsoils, particularly in soils with appreciable clay. Vertical water flow in well structured clay soils is mainly along preferred pathways.

The water flow along preferential pathways increases the frequency and amount of water draining below the root zone compared with a homogeneous soil. It provides a mechanism for preventing excess salt build up in soils in areas where the rainfall is appreciably less than the potential evaporation.

The spatial variations in soil structure mean that the salinity of water in the soil is not uniform. Plants have opportunities to extract water from more favourable locations, noting however, from a physical perspective this does not alter the water potential experienced by the plant. Indeed, in clay soils at very low water potentials the partitioning of salts in water can increase the osmotic effect of salt compared with the effect predicted by assuming all water is equally available to dissolve salts.

Degradation of soil structure associated with loss of organic matter turns a soil into a homogeneous porous medium. The salinity of the drainage water then tends to be in equilibrium with that of the soil hence transition from a well structured to a poorly structured soil increases the salinity of the drainage water. This effect can be reversed by improving the soil structure noting, however, that some structures such as large root channels take a long time to develop.

The decrease in percolation through the soil increases the surface saturation and thereby increases the potential for surficial lateral flow. The higher than normal salinity of this water due to the degradation of soil structure can produce high salinity where the water comes to the surface and/or accumulates.

One view expressed is that the CEC increase from humic materials, particularly the soluble humic and fulvic acids can be effective in buffering the effects of excessive solutes in the soil

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[15] pe is the Eh expressed as a concentration rather than activity and is directly comparable to pH.

solution. It is unclear what this buffering relates to but with current knowledge it does not reduce the osmotic effect of salts.

The presence of humic substances is identified as promoting the transmutation of the sodium ions (Pettit[16]). Transmutation reactions can occur within living organisms and involve combining two elements to form a new element, as with combining sodium with oxygen to form potassium or magnesium. Application of humins, humic acids, and fulvic acids to saline soils, in combination with specific microorganisms, reduces the concentration of sodium salts and the reduction is associated with an increase in concentration of other elements rather than leaching of sodium.

Conclusions

Soil organic matter plays a highly significant role in the prevention and development of adverse soil salinity. Its loss degrades the soil structure thereby reducing percolation, increasing runoff, and increasing the salinity of drainage water. Less water is available to plants and the quality of the water is reduced. Other changes include reduced aeration, and the storage and availability of plant nutrients.

Dryland salinity is usually a symptom of land degradation rather than the cause and addressing the prime cause, the loss of soil organic matter, provides production as well as environmental benefits. Dryland salinity is often readily reversible and its reversal improves the commercial viability of farming systems. It will also have social benefits in improving the viability of rural communities.

The NSF and WIB represent practical demonstrations of what can be achieved. In both situations the technology evolved through experience and observation. A key feature of the NSF is that the prime objective was improvement in animal wellbeing rather than simply improving the land. It identifies the inescapable link between the health of the land and the health of people.

The principles behind NSF, WIB and Keyline are not new having been practiced for thousands of years. The need to look to the past has arisen because actions last century addressed issues taken largely in isolation rather than in the context of the functioning of the system as a whole. The issue now is how to provide for general implementation. Few landholdings have streams and construction of large interceptor banks is not an ideal solution. Moreover, there would be considerable benefit in reducing the time needed for remediation. The need is widespread as more than 75% of farming soils are considered to have organic contents less than 1.75% when the desirable minimum is 2%.

The requirement is to develop a functional soil rather than continue to treat it as a hydroponic medium. There are means of rapidly improving the soil organic matter and the issue relates to the provision of practical means of implementation. Cost and time are of particular consequence. It is not simply a matter of spreading organic matter on soils as differences in climate, soil properties and the characteristics of organic matter determine the need to develop solutions specific to the circumstances. The provision of a comprehensive, cost-effective and generally applicable means of delivering solutions is the focus of Healthy Soils Australia (HSA) initiative.

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[16] Pettit, R. E. Organic matter, humus, humate, humic acid, fulvic acid, and humin: Their importance in soil fertility and plant health. http://www.previsemanufacturing.com/Library/Texas%20A&M%20Study.htm