A survey of the cation content of piggery effluents and some consequences of their use to irrigate soils

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Abstract. Piggery effluent contains high concentrations of potassium, and its repeated irrigation raises soil exchangeable potassium to levels, relative to divalent cations, that may degrade soil structure. We surveyed 6 big piggeries extending from south-eastern Queensland on a self-mulching Vertosol, to an Arenic Rudosol in south-eastern South Australia. We sampled effluent used for irrigation and also soil profiles to permit ‘fenceline’ comparisons between soils that had and had not been irrigated. The major water-soluble cations sodium (Na\textsuperscript{+}), potassium (K\textsuperscript{+}), calcium (Ca\textsuperscript{2+}), and magnesium (Mg\textsuperscript{2+}) were measured in the effluent and the soil saturation extracts, and also their exchangeable forms on air-dried soil samples. Ammonium-nitrogen (NH\textsubscript{4}\textsuperscript{+}-N) was also assayed. The effluents were similar, with pH values between 7.5 and 8 together with very high water-soluble NH\textsubscript{4}-N, lower values for K\textsuperscript{+} and Na\textsuperscript{+}, and quite low concentrations of Ca\textsuperscript{2+} and Mg\textsuperscript{2+}. Cation concentrations varied across effluents; sodium and potassium adsorption ratios (SAR and KAR) were relatively constant but smaller than an ammonium adsorption ratio (Am-AR), which we conceive to estimate the influence of NH\textsubscript{4}\textsuperscript{+}-N relative to the divalent cations in the effluent. Exchangeable K\textsuperscript{+} ratios in all profiles that had been irrigated were greater than their non-irrigated partners, as were the KAR values in their saturation extracts. Despite high concentrations of NH\textsubscript{4}\textsuperscript{+}-N and high values of Am-AR in the effluents, there was no evidence of exchangeable NH\textsubscript{4}\textsuperscript{+} in the soils when sampled, which, we presume, is rapidly taken up by plants or oxidised. We present data that support a useful relationship between total cation content and effluent and the soil saturation extract electrical conductivity (EC). We also observed a modest increase in the EC of the saturation extract of irrigated soils. Farm records were insufficient to permit material balance calculations.

Additional keywords: cation exchange, cation ratios, water soluble cations, electrical conductivity.

Introduction

High levels of potassium (K\textsuperscript{+}) in soils are believed to degrade soil structure, and plant production is reduced because the physical fertility of the soil is diminished. Piggery effluent has relatively high concentrations of K\textsuperscript{+} (Kruger et al. 1995; Biswas et al. 1999), and we were commissioned to determine levels of K\textsuperscript{+} in piggery waste and to see if general patterns of chemical and physical consequences of its application to soil might be discerned across a range of soils and climates from south-eastern Queensland to south-eastern South Australia. Redding et al. (2002) surveyed land management of agricultural, and specifically piggery-derived, effluents, and while they focussed on phosphorus, the general issues they identify in relation to effluent management apply to this paper as well. This paper focuses on the fate and effects of K\textsuperscript{+} on effluent properties and on possible soil physico-chemical trends associated with effluent irrigation. It describes some outcomes of a preliminary survey of 6 substantial piggeries where effluent has been applied systematically to the soil.

Literature on the nutritional significance of K\textsuperscript{+} is extensive (Munson 1985), as is that on the reaction chemistry of the element (e.g. Beckett 1964a, 1964b; Sparks and Huang 1985). There is, however, little information on the effects of K\textsuperscript{+} on soil structure beyond some early observations of its general physico-chemical similarity to sodium (Na\textsuperscript{+}) and the implication that their effects on soil structure would be similar (Richards 1954). Nevertheless, Biswas et al. (1999) state that ‘if K on the exchange sites exceeds 30\% then it behaves like Na and disperses clays’. This statement might be based on observations (Chen et al. 1983) on some effects of K\textsuperscript{+} on 2 Israeli soils.

We focused on 2 principal issues: (a) the distribution of K\textsuperscript{+} relative to other cations in effluents and its accumulation in soils to which effluents had been applied; and (b) possible soil physical effects of enhanced K\textsuperscript{+} levels in soils and...
effluents. Both of these issues are affected by soil and effluent cation ratios and concentrations, so it is useful to comment on the use of these ratios.

**Theory**

**Exchangeable cation ratios**

Exchangeable cations contribute to the material balance required to estimate the fate of cations added to the soil. In non-saline clay soils, for example, the sum of exchangeable cations may greatly exceed that of water-soluble cations and may dominate the exchange consequences of concentration, dilution, or leaching of the soil solution. In saline soils of low exchange capacity, their influence may be trivial. Models such as LEACHM (Hutson and Wagenet 1992) and UNSATCHEM (Suarez and Šimůnek 1997), which must predict reaction among competing cations, rely on selectivity coefficients or a Gapon exchange constant, \( \beta \), for the cation pairs in the system (Reiniger and Bolt 1972; Bolt et al. 1976; Robbins et al. 1980) with \( \beta_{\text{Na,Ca}} \) defined for Na\(^+\) and Ca\(^{2+}\), for example, by:

\[
\frac{\text{exNa}}{\text{exCa}} = \beta_{\text{Na,Ca}} \frac{[\text{Na}]}{\sqrt{[\text{Ca}]}} \tag{1}
\]

where braces, [], represent the solution concentrations of the cations in mmol\(_L\)\(^{-1}\). This equation is but one of several conventions (Bond 1995) used to describe exchange equilibria. Ideas of this sort also led Richards (1954) to use the sodium adsorption ratio, SAR, defined by:

\[
\text{SAR} = \frac{[\text{Na}]}{\sqrt{[\text{Ca}] + [\text{Mg}]}} \tag{2}
\]

and the potassium adsorption ratio, KAR, defined by:

\[
\text{KAR} = \frac{[\text{K}]}{\sqrt{[\text{Ca}] + [\text{Mg}]}} \tag{3}
\]

to illustrate, in their fig. 9, a relationship between the exchangeable sodium ratio, ESR (= exNa/(CEC – exNa)), and the SAR, and in their fig. 10 the corresponding exchangeable potassium ratio, EKR (= exK/(CEC – exK)), vs. KAR relation. These figures also show that K\(^+\) has a greater affinity for clay than does Na\(^+\) and that the EKR is almost an order of magnitude greater than the corresponding ESR for the same values of KAR and SAR. These solution ratios provide a useful first estimate of the consequences of the effluent and soil solution cation compositions in our study. However, exchangeable cation ratios are ‘peripheral’ to arguments relating to structural stability, because structural stability, insofar as it is affected by the dispersion or coagulation of the soil colloid, depends on the properties of the electrical double layer and thus on the equilibrium solution ratios and concentrations (cf. Verwey and Overbeek 1948; Hunter 1993).

**Water-soluble cation ratios and structural stability**

At a given soil solution salt concentration, soil structural stability decreases as levels of the monovalent cations sodium (Na\(^+\)) and potassium (K\(^+\)) increase relative to the divalent calcium (Ca\(^{2+}\)) and magnesium (Mg\(^{2+}\)). The effects reside in electrical double layer interactions and are parameterised in terms of the ratios and total concentrations of the cations in the ambient equilibrium solution. Quirk (2001) provides a recent discussion. Studies focussed on Na\(^+\) were initiated by Quirk and Schofield (1955), who set out the consequences of these interactions in terms of soil permeability and parameterised the chemistry in terms of (a) the exchangeable cation ratios and (b) the total equilibrium solution cation concentration. This convention derived from fig. 9 of Richards (1954). Subsequently, Collis-George and Smiles (1963) showed how the solution cation ratios and concentrations controlled the degree of dispersion or coagulation of illitic clay as double-layer theory anticipates. The coagulation or dispersion of the clay in turn affected the structural stability of a remoulded illitic soil, measured using the moisture characteristic method of Childs (1940). The data of Collis-George and Smiles correspond exactly with those of Quirk and Schofield (1955) through fig. 9 of Richards (1954). A review by Rengasamy and Sumner (1998) is based on the Quirk and Schofield approach, but Rengasamy et al. (1984), Oster et al. (1984), and Quirk (2001) adopt the approach of Collis-George and Smiles (1963), and Rengasamy et al. (1984) suggest a similar, but more conservative, separation between stable and precipitating suspensions of Red Brown Earths.

As we note above, there is little information about the effects of K\(^+\) in soil solutions, but table 1 of Verwey and Overbeek (1948) (reprinted in part as table 2.1 by Hunter 1993) shows that Na\(^+\) and K\(^+\) precipitate negatively charged As\(_2\)S\(_3\)-sols and Au-sols at almost the same concentrations, although the soil type is very important. We therefore infer that structurally critical values of SAR and KAR in equilibrium with similar total solution cation concentrations should themselves be similar for soils of similar mineralogy. Chen et al. (1983) indirectly supported this contention when they observed that ‘the degree of structural damage in soils containing 60–70% exchangeable K\(^+\) is comparable with that occurring with 10–16% exchangeable Na\(^+\)’. This comparison is insufficient to fully define double layer conditions for clay dispersion/coagulation because the soil solution concentrations are undefined, but we note, from Richards’ figures, that an EKR of 60–70% corresponds to a KAR of about 5.5–6.5, while an ESR of 10–16% corresponds to SAR of about 8–12.

We extend this argument to anticipate our measurements of unexpected high concentrations of NH\(_4\)\(^+\) in the effluents. There seem to be no data to guide us on the effects of monovalent relative to divalent cations on the stability of clay suspensions when NH\(_4\)\(^+\) and K\(^+\) dominate the cation suite;
nevertheless, a monovalent cation adsorption ratio (MCAR),
defined by:

\[
MCAR = \left(\frac{[\text{Na}]+[\text{K}]+[\text{NH}_4]}{\sqrt{([\text{Ca}]+[\text{Mg}])/2}}\right) (\text{mmol} \ell^{-1})^{1/2}
\]

provides a rational basis for assessing the initial effects of these effluents on soil structure. Its use is justified
qualitatively (\(a\)) by evidence in table 1 of Verwey and
Overbeek (1948) that the monovalent cations Na\(^+\) and K\(^+\)
flocculate a negatively charged colloid at similar
concentration, (\(b\)) because NH\(_4\)\(^+\) and K\(^+\) are of similar size
and thus of similar effect (Bolt et al. 1976), and (\(c\)) by
Richards’ (1954) use of the sum of divalent cations in the
denominator of SAR and KAR as a way to account for them.

Finally, we reiterate that Eqns 2 and 3, together with an
analogous relation for NH\(_4\)\(^+\) (Eqn 5 defined below), provide
rational bases to estimate exchange among competing cation
sets and, with the total solution cation concentration, also
provide guidance on chemically moderated structural
stability. They also permit comparison with the USDA
database of Richards (1954).

Experimental

Site selection, descriptions, and sampling

Six piggeries were selected to represent a range of soils and climates. Each
piggery has carried >1500 sows for a decade or more. Physical
boundaries between irrigated and non-irrigated areas were
distinguished confidently, but in contrast with experiences of Redding
et al. (2002), operators’ records of effluent application and field
histories were uncertain.

Farm information

Farm 1

This farm is located in the south-east uplands of climatic Zone 5
(Thackway and Cresswell 1992) with an average annual rainfall of
648 mm. It has been lightly managed for >10 years. Effluent application
rates have been light and various ways to manage effluent have been
explored. Analysis and nutrient values of liquids and solids are
available. Liquid and solid are separated in contour sedimentation
channels and liquid is ponded there until it is irrigated. The solid is
dried in the sun and some sold as compost. A cropping cycle seeks to
remove excess nutrients associated with effluent irrigation. Existing
farm records do not permit nutrient balance calculations.

Farm 2

This farm is in the Coastal Warm Temperate area of climatic Zone
6 (Thackway and Cresswell 1992) with an average annual rainfall of
719 mm. On this farm, effluent has been applied to approximately
100 ha of kikuyu pasture for almost 30 years. Effluent application rates
as great as 500 m\(^3\)/day were once applied but present rates lie in the
range 150–200 m\(^3\)/day. Most areas are grazed but some silage/hay has
been taken from about 50% of paddocks. The soils and effluents are
routinely monitored but the data do not permit estimates of material
balance.

Farm 3

This farm is in the Coastal Warm Temperate area of climatic Zone
6 (Thackway and Cresswell 1992) with an average annual rainfall of
647 mm. Effluent has been applied here to approximately 95 ha of
pasture, including some lucerne, for approximately 30 years. Both solid
and liquid have been applied but local rates are uncertain. Solid is now
compounded with the intention of sale off-site. Liquid effluent is sprayed
and treated areas are cropped and grazed. Managers assert that good
production follows effluent application and they now seek to achieve
nutrient balance, although anecdotally, this has not always been so.
Soils are routinely monitored but we cannot compare effluent treated
and untreated areas from available data.

Farm 4

This farm is in an area transitional from Wet/Dry Monsoon to
Central Arid of climatic Zone 8 (Thackway and Cresswell 1992) with
an average annual rainfall of 673 mm. Effluent has been applied for
6 years to approximately 80 ha of cropping land, which is
double-cropped if the weather permits. Neighbours also use substantial
amounts of effluent. Previously, coarse-textured sloping land adjacent
to the piggery was used. This land is now rested and all material is
applied to heavy clay (Vertosol) alluvial flats. Both the coarser texture
and the heavy clays soils were sampled. Good current records of
effluent application are maintained on this property; however, in the
absence of export data, they do not permit us to assess effects of effluent
application.

Farm 5

This farm is in an area transitional from Mediterranean to Central
Arid of climatic Zone 3 (Thackway and Cresswell 1992) with an
average annual rainfall of 540 mm. Sampling sites are in, or adjacent to,
approximately 120 ha of cropping land where effluent has been applied
heavily under a centre pivot system for 7 years. Effluent has been used
to satisfy the water demand of the crop, and maize/sorghum has been
used to export nutrients. Excellent current records are maintained on
this property, but they do not permit us to assess the long-term effects
of effluent application.

Farm 6

This farm is in the Mediterranean area of climatic Zone 2
(Thackway and Cresswell 1992) with an average annual rainfall of
702 mm. Effluent has been applied to approximately 80 ha of cropping
land under a centre pivot system for 6–8 years. Soils are deep,
well-draining sands and maize is used to export nutrients from the site.
Much thought has been devoted to sustainable waste management in
this enterprise. Solids are separated from the liquids using a screw
press. The liquid effluent is diluted by up to 1:20 before irrigation and
the solid is composted with vegetable matter obtained off-site and sold
to help establish perennial horticultural crops. Routine soil analysis is
carried out, but again, data do not permit us to assess the material
balance.

Sampling procedure

Within each farm, 2 or 3 contrasting pairs of profiles were sampled that
had, and had not, received effluent. This discrimination was based on
fence lines separating spray irrigation ‘treatments’ or, in 2 cases, on
soils beneath and beyond centre pivot irrigators. Four or five
50-mm-diameter cores were taken within each treatment and bulked
according to depth. Sampling depths tended to be in 50-mm increments
to 250 mm and thereafter at 100-mm increments to about 0.7 m. We
ensured that complementary pairs of soil profiles that had and had not been irrigated were sampled at similar depth increments to assist comparison. Representative soil profiles at all sites were described and classified (McDonald et al. 1990).

Supernatant samples were also taken from effluent ponds being used for irrigation. These were stored frozen until analysed. We also collected previous effluent and soil analyses to help interpret changes resulting from effluent irrigation.

**Laboratory methods**

**Effluent analysis**

Water-soluble cations Na\(^+\), K\(^+\), Ca\(^{2+}\), and Mg\(^{2+}\) were measured using inductively coupled plasma (ICP) spectroscopy. NH\(_4^+\) was measured by reaction with hypochlorite liberated from dichlor-isocyanurate under alkaline conditions. The absorbance was measured at 660 nm using a dual-channel segmented flow analyser. The pH and electrical conductivity (EC) were also measured and Cl\(^-\), NO\(_3^-\), and SO\(_4^{2-}\) were measured using ion-chromatography. Alkalinity (as HCO\(_3^-\)) of the effluents was calculated from the pH assuming the effluent was in equilibrium with the CO\(_2\) in the atmosphere (Lindsay 1979).

**Soil analysis**

The saturation extract (Method 2D1 of Rayment and Higginson 1992) was analysed for Na\(^+\), K\(^+\), Ca\(^{2+}\), and Mg\(^{2+}\). The pH and EC were also measured on the saturation extracts from all samples, together with Cl\(^-\), NO\(_3^-\), and SO\(_4^{2-}\) were measured using ion-chromatography. Alkalinity (as HCO\(_3^-\)) of the effluents was calculated from the pH assuming the effluent was in equilibrium with the CO\(_2\) in the atmosphere (Lindsay 1979).

**Statistical analysis**

Changes in the soil properties were analysed using GENSTAT 5 (Payne 1993). Main effects included in the block and treatment model were farm, soil classification, irrigation, depth, and replicates within the farm (Table 3). It was convenient to cluster depths into the increments 0–100, 100–200, and 200–450 mm. Data graphed for illustrative purposes are averages of the cluster for each farm, treatment, and depth.

**Results and discussion**

**The effluents**

Table 1 shows chemical analyses of effluents from the farms surveyed. The table also presents historical data ranges from previous analyses. The methods used to derive these historical data are uncertain and their precision is unknown but their values support our general conclusions that effluents tended to be similar across all farms. This is not surprising in view of the similar basic diets for pigs in intensive systems, together with generally similar flushing procedures used to clear dung and urine from the pens. At the same time, concentration variations were evident that reflect climatic conditions prior to sampling in the spring of 2000 and also variation in reuse of effluent as wash-down water.

We discuss the effluent data first with reference to arbitrary values that approximate those used by environmental protection authorities to classify effluents intended for irrigation. Table 2 sets out indicative critical values of key characteristics.

**Cation concentrations**

Cation concentrations were high, with NH\(_4^+\) the most abundant, followed by K\(^+\) then Na\(^+\), while Ca\(^{2+}\) and Mg\(^{2+}\) concentrations were relatively modest. The high values of NH\(_4^+\) suggest that treatment systems were generally overloaded and anoxic. This seems to be a common feature

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**Table 1. Selected piggery effluent characteristics**

<table>
<thead>
<tr>
<th>Farm 1</th>
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<tbody>
<tr>
<td>EC</td>
<td>pH</td>
<td>HCO(_3^-)</td>
<td>Cl(^-)</td>
<td>NO(_3^-)</td>
<td>S</td>
<td>NH(_4^+)</td>
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<tr>
<td>6.1</td>
<td>7.6</td>
<td>1.8</td>
<td>10.4</td>
<td>&lt;0.1</td>
<td>0.7</td>
<td>48.6</td>
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<td>9.5</td>
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<td>Farm 2</td>
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<tr>
<td>5.1</td>
<td>7.8</td>
<td>2.9</td>
<td>6.8</td>
<td>&lt;0.1</td>
<td>0.6</td>
<td>50.0</td>
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<td></td>
<td>40–46</td>
<td>3–4</td>
<td>10–11</td>
<td>0.7–0.8</td>
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<td>Farm 3</td>
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<td>4.8</td>
<td>7.9</td>
<td>3.6</td>
<td>12.1</td>
<td>&lt;0.1</td>
<td>1.7</td>
<td>23.6</td>
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<td>4–8</td>
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<td>7.7–9</td>
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<td>Farm 4</td>
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<tr>
<td>8.4</td>
<td>7.6</td>
<td>1.8</td>
<td>13.2</td>
<td>&lt;0.1</td>
<td>1.9</td>
<td>65.0</td>
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<tr>
<td>6–8</td>
<td>7.7–9</td>
<td></td>
<td>7–12</td>
<td>3–4</td>
<td>8–13</td>
<td>1–4</td>
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<tr>
<td>Farm 5</td>
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<td></td>
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<tr>
<td>4.3</td>
<td>8.2</td>
<td>7.2</td>
<td>10.4</td>
<td>&lt;0.1</td>
<td>1.7</td>
<td>25.0</td>
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<tr>
<td>5–9</td>
<td>8–9</td>
<td>17</td>
<td></td>
<td></td>
<td>21–62</td>
<td>1–5</td>
</tr>
</tbody>
</table>

\( ^{\text{a}}\text{Calculated from the pH and assuming the effluent is in equilibrium with CO}_2\text{ in the atmosphere (Lindsay 1979).} \)
of piggery effluents worldwide (Bernal et al. 1993; Sloan et al. 1999; Pote et al. 2001). The effects of these high concentrations of NH$_4^+$ are important and are discussed later.

**Cation ratios**

The effluent SAR shown in Table 1 was in the range 3.7 < SAR (mmol/L)$^{1/2}$ < 11.4. According to conventions summarised by Kruger et al. (1995), values of SAR in the range 6–8 present problems that can be ameliorated with gypsum, but irrigation with waters with SAR >8 is not generally recommended. Richards’ (1954) fig. 9 implies that, at an SAR of 8, in the absence of cations other than Ca$^{2+}$, Na$^+$ will occupy about 10% of the exchange sites.

The effluent values of KAR were somewhat greater (8.7–14), with an average of about 10 (mmol/L)$^{1/2}$. Richards’ (1954) fig. 10 suggests that a KAR value of 10 will be associated with an exchangeable K$^+$ percentage of >50% and that exchangeable Ca$^{2+}$ and Mg$^{2+}$ will be substantially reduced by sustained effluent irrigation.

We also defined and tabulated an ammonium adsorption ratio, Am-AR, analogous to SAR and KAR, viz.:

$$\text{AmAR} = \frac{[\text{NH}_4^+]}{\sqrt{([\text{Ca}] + [\text{Mg}])/2}} \text{ (mmol/L)}^{1/2}$$

The smallest tabulated value of AmAR was 15.8 and the average of our measurements was 36. Because of the similarity between K$^+$ and NH$_4^+$, we infer that such high numbers must result in relatively large amounts of exchangeable NH$_4^+$ following irrigation.

Our focus on the solution cation ratios and concentrations reflects their central role as determinants of structural stability.

**Colloid dispersion and structural stability**

Figure 1 shows values of SAR, KAR, AmAR, and MCAR (mmol/L)$^{1/2}$, graphed against the total cation concentration. Also shown are the Collis-George and Smiles (1963) relation (which matches data of Quirk and Schofield 1955) and the relationship that Rengasamy et al. (1984) derived for Red Brown Earths in Australia. These define dispersion or coagulation in kaolinite/illites and hence influence the structural stability of the soil. Smectites tend to be more stable. In terms of the SAR, all effluents would be regarded as stable using the Rengasamy criteria. Similarly, KAR and AmAR values by themselves would appear to imply stability if the Rengasamy criteria are any guide. The MCAR data appear problematic, however, and while all effluent data lie below the ‘coagulation’ line of Collis-George and Smiles (1963), the situation using the Rengasamy et al. (1984) criteria is less clear-cut. Nevertheless, dispersion tests with soils confirm that the clay is flocculated in solutions of similar cation constitution. We reiterate that none of these effluents would be expected to cause clay to disperse if we use criteria, restricted to sodium, of Rengasamy et al. (1984) or the more relaxed criteria of Collis-George and Smiles (1963). These issues are discussed below in the context of the soils data as well as in the Appendix, but require further study.

**Subsidiary issues affecting effluent irrigation**

**Electrical conductivity**

Australian environmental protection agencies (see e.g. Anon. 1995) set limits to irrigation waters summarised in fig. 4 on p. 158 of Kruger et al. (1995). In terms of these criteria, all effluents were saline (4 < EC (dS/m) < 10) and are unsuitable for irrigation unless soils are very permeable and crops are highly salt-tolerant.

**pH values**

The pH values tended to lie between 7.6 and 8, but with one value >9. These values also exceed levels generally acceptable in irrigation waters.
Anions

The total cation charge substantially exceeded that of the measured anions (Cl\(^-\), SO\(_4^{2-}\), and NO\(_3^-\)). HCO\(_3^-\) estimated from the pH and assuming the system to be in equilibrium with CO\(_2\) in the atmosphere (Lindsay 1979) was insufficient to account for the difference between cations and anions, which we must attribute to phosphate (Redding et al. 2002). There was no measurable NO\(_3^-\) (Table 1).

The role of NH\(_4^+\)

The complicating element in these discussions is the role and fate of NH\(_4^+\) in the effluent. This cation is not seen as a significant component of ‘normal’ irrigation water; it rarely features in criteria used to assess water suitability for irrigation, and most authors tend to ignore its influence to focus on the 4 alkaline cations (but see de Haan and Zwerman 1976). High values of AmAR (Eqn 5) associated with high concentrations of NH\(_4^+\) in the effluent, however, led us to expect, initially, a very high exchangeable NH\(_4^+\) ratio. This effect will be moderated by volatilisation, which Kruger et al. (1995) estimated to represent about 20% of that in the pond liquor. Nevertheless, a decrease of even 50% in AmAR from values as great as 36 still represents a large load of a competitive cation. Subsequently, oxidation to NO\(_3^-\) or uptake of the NH\(_4^+\)-N will occur. This will affect our interpretation of the significance of both the EC and the pH in relation to the suitability of these effluents for irrigation, so critical values of EC that reflect the long-term consequences of irrigation with effluents are required. Explicitly, EC values that are so dominated by high concentrations of NH\(_4^+\) should be considered more flexibly than those where Na\(^+\) is dominant and it may be more appropriate to calculate a corrected EC based only on the 4 alkaline cations and use this value to assess the suitability of the effluent for irrigation.

Soil characteristics

All farms initially asserted that they held good records of paddock treatment but it emerged that only one retained quantitative records, and even there, it was impossible to attempt an accurate material balance for K\(^+\) or other cations because of local climatic variability, uncertain effluent concentration histories and application rates, and uncertain commodity removal. Farms 2, 3, 4, and 5, for example, had irrigated relatively heavily for more than 10 years. Farms 2, 3, and 4 were grazed with some cropping and commodity removal. Farm 5 maintained an intensive cropping program. Despite these uncertainties, data comparing irrigated and non-irrigated profiles remain useful, but because of the ranges of soils, climate, and treatments selected in this survey, we sought general trends here and defer detailed analyses of well-defined cases to later papers.
We look first at ‘general’ properties of the soils, then at
the specific issues of Na⁺, K⁺, and NH₄⁺ in the saturation
extract, and then the exchangeable cations.

Soil classification

Classifications of the soils encountered in this survey are
shown in Table 3, which also identifies the surface soil clay
content and mineralogy determined by X-ray diffraction.
Detailed profile descriptions are available in the CSIRO
National Soils Data Base. In terms of Northcote’s Principal
Profile Forms, soils varied from uniform, heavy clay,
self-mulching soils (Vertosols) through texture contrast soils
to uniform sandy soils (Arenic Rudosols).

Saturation extract cation ratios

It is useful to illustrate this dataset graphically as well as
in tabular form. We ensured that complementary pairs of soil
profiles that had and had not been irrigated were sampled at
the same depth increments to provide a basis for comparison.
For any attribute of concern, we plotted the value of the
non-irrigated variant at any depth as the ordinate, and the
value for the irrigated partner as the abscissa, in rectangular
coordinates. If no change were associated with irrigation, the
point would plot on the 1:1 diagonal; displacement from this
line is interpreted as a ‘consequence’ of irrigation. Figures 2
and 3 show the effects of irrigation on KAR and SAR.

There was evidently a general increase in these ratios
associated with irrigation, with the greatest effects at the
heavily irrigated Farms 2 and 5. Farms 3 and 4, associated
with heavy clays, showed little increase, and Farms 1 and 6,
where application has been modest or the effluent diluted
before irrigation, showed little effect.

Table 4 deals with these data statistically and relates the
KAR, SAR, and MCAR of the saturation extract of the
irrigated soils to those of their non-irrigated partners. We
reiterate that by the time these soils were sampled, all trace
of NH₄-N had disappeared, so MCAR was the sum of KAR
and SAR. The farms differed significantly (P < 0.001) and
there were also differences associated with irrigation (P <
0.01). At Farms 2 and 5, the increase in cation ratios in
association with effluent application was significant (P <
0.01) and extended down the profiles. In particular, SAR
tended to increase with depth in irrigated soils and may have
reflected the displacement of Na⁺ by NH₄⁺ and K⁺
immediately following irrigation. The chromatographic
chemistry of this process will be published separately. At
Farm 1 there was an apparent, though modest, increase in the
cation ratios, whereas at the other farms there was no
significant effect. In no soil did the KAR and SAR of the
saturation extract approach effluent values.

Saturation extract ECₑ

Table 5 shows that there was an effect of irrigation on ECₑ
between farms (P < 0.001) and clear effects associated with
effluent irrigation (P < 0.001). Explicitly, Farms 2, 5, and 6
revealed significant increases in ECₑ between the irrigated
and non-irrigated profiles (P < 0.001), and in Farms 2 and 5,
ECₑ values of the irrigated soils increased with depth. There
was no significant effect among the other farms, although
ECₑ values generally tended to decrease with increasing

---

Table 3. Soil classification and clay mineralogy, climatic zone, and qualitative effluent loading

Further detail on these soils is found in the CSIRO National Soils Database [contact: david.jacquier@csiro.au]. Site 5 is identified as CP 338 and 339. The others are found under Project Code PRDC1

<table>
<thead>
<tr>
<th>Farm (site)</th>
<th>Australian Soil Classification</th>
<th>Topsoil clay</th>
<th>Clay mineral</th>
<th>Climatic Zone</th>
<th>Soil grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(1,2,3)</td>
<td>Red Chromosol [deep]</td>
<td>10–20%</td>
<td>75% kaolinite; 20% illite</td>
<td>Zone 5; SE Uplands</td>
<td>1</td>
</tr>
<tr>
<td>2(1)</td>
<td>Red Kurosol [deep]</td>
<td>20–25%</td>
<td>55% kaolinite; 20% illite</td>
<td>Zone 6; Coastal, Warm, Temperate</td>
<td>2</td>
</tr>
<tr>
<td>2(2)</td>
<td>Yellow Chromosol [moderately deep]</td>
<td>25–30%</td>
<td>NA</td>
<td>Zone 6; Coastal, Warm, Temperate</td>
<td>2</td>
</tr>
<tr>
<td>3(1)</td>
<td>Brown Chromosol [very deep]</td>
<td>20–30%</td>
<td>80% smectite</td>
<td>Zone 6; Coastal, Warm, Temperate</td>
<td>3</td>
</tr>
<tr>
<td>3(2)</td>
<td>Brown Dermosol [deep]</td>
<td>14–20%</td>
<td>NA</td>
<td>Zone 6; Coastal, Warm, Temperate</td>
<td>3</td>
</tr>
<tr>
<td>4(1)</td>
<td>Self-mulching Vertosol</td>
<td>50–60%</td>
<td>95% smectite</td>
<td>Zone 8; Wet/Dry Monsoon transition to Central Arid</td>
<td>4</td>
</tr>
<tr>
<td>4(2)</td>
<td>Yellow Chromosol</td>
<td>10%</td>
<td>NA</td>
<td>Zone 8; Wet/Dry Monsoon transition to Central Arid</td>
<td>2</td>
</tr>
<tr>
<td>5(1,2)</td>
<td>Red Chromosol [very deep]</td>
<td>15–20%</td>
<td>50% kaolinite; 20% illite</td>
<td>Zone 3; Mediterranean transition to Central Arid</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Arenic Rudosol</td>
<td>1–2%</td>
<td>60% amorphous</td>
<td>Zone 2; Mediterranean</td>
<td>5</td>
</tr>
</tbody>
</table>

depth. Generally, no soil presented serious salinity problems. In all cases EC_e was substantially less than that of the effluent, EC_w, shown in Table 1, and no soil had measurable levels of water-soluble NH_4^+ when sampled. These observations are consistent with our suggestion that the EC_w of the effluents might be operationally ‘discounted’ for the NH_4^+ that it contains.

**EC_e v. soluble cations in the saturation extract**

Figure 4 shows the relationship between water-soluble cation concentration and EC_e, using data measured on the saturation extracts for all samples across soils ranging from Arenic Rudosols to self-mulching Vertosols. We expected such a relationship because the solution conductivity is a
Cation content of piggery effluent

consequence of the activity of a population of ions over practical ranges of concentration (McNeal et al. 1970; Marion and Babcock 1976; Lindsay 1979; Sposito 1989). Richards (1954) published a similar dataset for Californian soils, and Rengasamy and Sumner (1998) (for example) cite it. The total dataset in Fig. 4 has the equation: 

\[
\log_{10}(C/(\text{mmol} /L)) = (1.007 \pm 0.004) + 
(1.012 \pm 0.007) \log_{10}(\text{EC}_e/(\text{dS/m}))
\]  

(6)

with \( R^2 = 0.99 \). It varies slightly from the ‘approximate average line’ of Richards, which has the same intercept but a slope of 1.093, but corresponds very closely with, and is marginally better than, eqn 9 of Rengasamy et al. (1984), which represents data from their study of Red Brown Earths in Australia. The excellence of this relationship implies that the comments above on the EC_e data apply also to the total soluble cation relations within and between soils and ‘treatments’. This graph also presents the effluent data of Table 1 and includes, in the soluble cation concentration, the contribution of NH_4^+.

### Structural stability criteria

Figure 5 relates MCAR to the total cation concentration for the saturation extract data. As with previous general relationships, different soils and treatments behaved

Table 4. Effect of effluent irrigation on KAR, SAR, and MCAR (\(\text{mmol} /L\)^{1/2}) of the saturation paste extracts of the soils with depth in the profile

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Farm (soil group)</th>
<th>KAR Irrigated</th>
<th>Non-Irrigated</th>
<th>SAR Irrigated</th>
<th>Non-Irrigated</th>
<th>MCAR Irrigated</th>
<th>Non-Irrigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–100</td>
<td>1 (1)</td>
<td>2.08</td>
<td>1.23</td>
<td>0.47</td>
<td>0.29</td>
<td>2.55</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>2 (2)</td>
<td>8.29</td>
<td>1.85</td>
<td>3.00</td>
<td>0.38</td>
<td>11.00</td>
<td>2.23</td>
</tr>
<tr>
<td></td>
<td>3 (3)</td>
<td>2.76</td>
<td>3.29</td>
<td>1.90</td>
<td>2.56</td>
<td>4.67</td>
<td>5.86</td>
</tr>
<tr>
<td></td>
<td>4 (4)</td>
<td>0.23</td>
<td>0.33</td>
<td>2.25</td>
<td>3.08</td>
<td>2.49</td>
<td>3.42</td>
</tr>
<tr>
<td></td>
<td>4 (2)</td>
<td>4.80</td>
<td>2.89</td>
<td>3.25</td>
<td>0.18</td>
<td>8.05</td>
<td>3.07</td>
</tr>
<tr>
<td></td>
<td>5 (1)</td>
<td>7.98</td>
<td>0.57</td>
<td>5.01</td>
<td>1.17</td>
<td>13.00</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td>6 (5)</td>
<td>0.57</td>
<td>0.81</td>
<td>3.46</td>
<td>0.86</td>
<td>4.03</td>
<td>1.67</td>
</tr>
<tr>
<td>s.e.d</td>
<td></td>
<td>1.89</td>
<td></td>
<td>0.92</td>
<td></td>
<td>2.04</td>
<td></td>
</tr>
<tr>
<td>100–200</td>
<td>1 (1)</td>
<td>1.38</td>
<td>0.90</td>
<td>0.79</td>
<td>0.48</td>
<td>2.18</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>2 (2)</td>
<td>3.77</td>
<td>1.10</td>
<td>4.03</td>
<td>0.67</td>
<td>7.81</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>3 (3)</td>
<td>1.76</td>
<td>1.47</td>
<td>2.45</td>
<td>2.67</td>
<td>4.22</td>
<td>4.15</td>
</tr>
<tr>
<td></td>
<td>4 (4)</td>
<td>0.09</td>
<td>0.11</td>
<td>4.36</td>
<td>6.94</td>
<td>4.46</td>
<td>7.06</td>
</tr>
<tr>
<td></td>
<td>4 (2)</td>
<td>3.90</td>
<td>2.14</td>
<td>3.86</td>
<td>0.33</td>
<td>7.76</td>
<td>2.46</td>
</tr>
<tr>
<td></td>
<td>5 (1)</td>
<td>7.37</td>
<td>0.20</td>
<td>5.63</td>
<td>1.84</td>
<td>13.10</td>
<td>2.03</td>
</tr>
<tr>
<td></td>
<td>6 (5)</td>
<td>0.24</td>
<td>0.44</td>
<td>3.49</td>
<td>0.99</td>
<td>3.73</td>
<td>1.43</td>
</tr>
<tr>
<td>s.e.d</td>
<td></td>
<td>0.68</td>
<td></td>
<td>1.42</td>
<td></td>
<td>1.44</td>
<td></td>
</tr>
<tr>
<td>200–450</td>
<td>1 (1)</td>
<td>1.38</td>
<td>0.96</td>
<td>0.79</td>
<td>0.59</td>
<td>2.18</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>2 (2)</td>
<td>3.01</td>
<td>0.21</td>
<td>6.97</td>
<td>2.15</td>
<td>9.98</td>
<td>2.36</td>
</tr>
<tr>
<td></td>
<td>3 (3)</td>
<td>1.35</td>
<td>0.68</td>
<td>6.07</td>
<td>4.56</td>
<td>7.00</td>
<td>5.25</td>
</tr>
<tr>
<td></td>
<td>4 (4)</td>
<td>0.05</td>
<td>0.10</td>
<td>7.09</td>
<td>10.8</td>
<td>7.14</td>
<td>10.93</td>
</tr>
<tr>
<td></td>
<td>4 (2)</td>
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<td>2.54</td>
<td>1.80</td>
<td>0.41</td>
<td>4.25</td>
<td>2.95</td>
</tr>
<tr>
<td></td>
<td>5 (1)</td>
<td>6.56</td>
<td>0.20</td>
<td>6.97</td>
<td>2.32</td>
<td>13.54</td>
<td>2.53</td>
</tr>
<tr>
<td></td>
<td>6 (5)</td>
<td>0.21</td>
<td>0.33</td>
<td>2.71</td>
<td>0.85</td>
<td>2.92</td>
<td>1.18</td>
</tr>
<tr>
<td>s.e.d</td>
<td></td>
<td>0.93</td>
<td></td>
<td>3.35</td>
<td></td>
<td>3.17</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Effect of effluent irrigation on \(\text{EC}_e\) (dS/m) of the saturation paste extracts of the soils with depth in the profile

<table>
<thead>
<tr>
<th>Farm (soil group)</th>
<th>0–100 mm</th>
<th>100–200 mm</th>
<th>200–450 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Irrigated</td>
<td>Non-irrigated</td>
</tr>
<tr>
<td>1 (1)</td>
<td>0.52</td>
<td>0.46</td>
<td>0.31</td>
</tr>
<tr>
<td>2 (2)</td>
<td>4.49</td>
<td>1.66</td>
<td>4.65</td>
</tr>
<tr>
<td>3 (3)</td>
<td>1.27</td>
<td>2.08</td>
<td>0.84</td>
</tr>
<tr>
<td>4 (4)</td>
<td>1.80</td>
<td>3.42</td>
<td>2.29</td>
</tr>
<tr>
<td>4 (2)</td>
<td>2.53</td>
<td>1.11</td>
<td>1.53</td>
</tr>
<tr>
<td>5 (1)</td>
<td>1.44</td>
<td>0.39</td>
<td>1.91</td>
</tr>
<tr>
<td>6 (5)</td>
<td>1.90</td>
<td>0.65</td>
<td>1.70</td>
</tr>
<tr>
<td>S.e.d</td>
<td>0.56</td>
<td>0.71</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4. The electrical conductivity, $EC_e$ (dS/m), of the saturation extracts of all soil samples related to their sum of cations. $EC_w$ data for the effluent (including the high concentration of NH$_4^+$) are also included and identified by open squares. This dataset is effectively co-linear with that of fig. 4 of Richards (1954) and consistent with eqn 9 of Rengasamy et al. (1984) for Red Brown Earths. The equation of the line fitting these data ($r^2 = 0.99$) is:

$$\log_{10}\left(\frac{C}{(\text{mmol/L})}\right) = (1.007\pm0.004)+(1.012\pm0.007)\log_{10}\left(\frac{EC_e}{(\text{dS/m})}\right)$$

Fig. 5. The monovalent cation adsorption ratio (MCAR (mmol c/L)$^{1/2}$) of the soil saturation extracts graphed as a function of their total solution cation concentration. The upper straight line was derived by Collis-George and Smiles (1963) to discriminate between dispersed sodic illite suspensions; the lower one was derived by Rengasamy et al. (1984) for Red Brown Earths (cf. Fig. 1).
differently. Relative to the Collis-George and Smiles (1963) line, all soils appeared to be structurally stable at the saturation paste water content but it is evident that the status of soils in the different farms was different. The Rengasamy et al. (1984) ‘stability line’ suggests that irrigated soils at Farms 3 and 5 are potentially unstable, although high organic matter at Farm 3 masks this. These observations are consistent with field observation and with a dataset presented in Appendix 1. We offer no further generalisations in this regard but note that the concentration of this extract implies that, in their natural state, these soils must have a greater fraction of exchangeable monovalent cations than the saturation extract concentrations imply because an increase in concentration increases the influence of the monovalent

![Fig. 6](image_url)

**Fig. 6.** The association between effluent irrigation and the exchangeable potassium ratio (EKR) and graphed according to the convention described in the text. Points above the 1:1 line represent an increase in EKR associated with irrigation; those below represent a decrease.

![Fig. 7](image_url)

**Fig. 7.** The association between effluent irrigation and the exchangeable sodium ratio (ESR) graphed according to the convention described in the text. Points above the 1:1 line represent an increase in ESR associated with irrigation; those below represent a decrease.
cations according to their concentration, while the influence of the divalent cations increases according to the square root of their concentration. The effect is moderated by the relative amounts of exchangeable and water soluble cations (Collis-George and Smiles 1963; Bolt et al. 1976).

The exchangeable cation ratios

The EKR and ESR complemented KAR and SAR data, and again, data are graphed as well as tabulated. Figures 6 and 7 use the same convention as Figs 2 and 3 to compare irrigated and non-irrigated soils, and EKR data for Farms 2 and 5, in particular, reveal substantial effects of irrigation. Comparison of these figures proved EKR to be a very sensitive indicator of irrigation with effluent containing K+, while ESR was relatively insensitive. The difference arises because slopes of the ‘isotherms’ shown, for example, as figs 9 and 10 of Richards (1954), are quite different. Note too, in the case of Farm 5, that EKR values consistent with the effluent KAR and the Richards (1954) isotherm were approached.

Table 6 statistically relates the EKR and ESR of comparable irrigated and non-irrigated horizons to discriminate between the irrigated soils and their non-irrigated partners. Differences between soils were significant, and Farms 1, 2, 4, and 5 showed significant increases in KAR in the surface 100 mm. In Farms 1 and 2 these effects are seen to depth, and in Farm 5 KAR increases significantly with depth. ESR changes were marginal in all soils.

Regrettably, Tables 4 and 6 are formally unrelated because the exchangeable cations were measured at air-dry water content and dilution of the soil water to produce the saturation extract perturbs the distribution of the water-soluble and exchangeable cations according to their exchange isotherms and the amount of charge in solution relative to the cation exchange capacity.

Subsidiary observations

Subsidiary data comparing the effects of irrigation are summarised in Table 7.

The soil pH

Table 7 compares the pH of irrigated soil 1:5 extract in 0.01 M CaCl₂ with that of its non-irrigated partner. Although all effluents were alkaline, there was no particular consequence of irrigation on the surface pH or on the pH trend in the soil profiles that might be associated with effluent irrigation. Redding et al. (2002) made similar

<table>
<thead>
<tr>
<th>Farm (soil group)</th>
<th>EKR</th>
<th>ESR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–100 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (1)</td>
<td>0.129</td>
<td>0.083</td>
</tr>
<tr>
<td>2 (2)</td>
<td>0.249</td>
<td>0.131</td>
</tr>
<tr>
<td>3 (3)</td>
<td>0.189</td>
<td>0.190</td>
</tr>
<tr>
<td>4 (4)</td>
<td>0.028</td>
<td>0.040</td>
</tr>
<tr>
<td>4 (2)</td>
<td>0.150</td>
<td>0.100</td>
</tr>
<tr>
<td>5 (1)</td>
<td>0.36</td>
<td>0.09</td>
</tr>
<tr>
<td>6 (5)</td>
<td>0.022</td>
<td>0.047</td>
</tr>
<tr>
<td>s.e.d</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>100–200 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (1)</td>
<td>0.151</td>
<td>0.094</td>
</tr>
<tr>
<td>2 (2)</td>
<td>0.336</td>
<td>0.102</td>
</tr>
<tr>
<td>3 (3)</td>
<td>0.152</td>
<td>0.124</td>
</tr>
<tr>
<td>4 (4)</td>
<td>0.012</td>
<td>0.010</td>
</tr>
<tr>
<td>4 (2)</td>
<td>0.195</td>
<td>0.110</td>
</tr>
<tr>
<td>5 (1)</td>
<td>0.442</td>
<td>0.081</td>
</tr>
<tr>
<td>6 (5)</td>
<td>0.013</td>
<td>0.031</td>
</tr>
<tr>
<td>s.e.d</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>200–450 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (1)</td>
<td>0.201</td>
<td>0.121</td>
</tr>
<tr>
<td>2 (2)</td>
<td>0.330</td>
<td>0.041</td>
</tr>
<tr>
<td>3 (3)</td>
<td>0.117</td>
<td>0.064</td>
</tr>
<tr>
<td>4 (4)</td>
<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>4 (2)</td>
<td>0.175</td>
<td>0.165</td>
</tr>
<tr>
<td>5 (1)</td>
<td>0.590</td>
<td>0.080</td>
</tr>
<tr>
<td>6 (5)</td>
<td>0.021</td>
<td>0.032</td>
</tr>
<tr>
<td>s.e.d</td>
<td>0.07</td>
<td>0.06</td>
</tr>
</tbody>
</table>
observations. At the same time there were systematic trends in some soils. Farm 6 soils were almost pure sand with no buffering capacity and their pH increased throughout the profile \((P < 0.01)\). The pH of soils at Farms 1 and 2 (Chromosols and Kurasols) seemed to decrease (the latter significantly) as did the subsoil for Farm 5 (Chromosols), but patterns were irregular. These effects will be associated with oxidation of \(\text{NH}_4^+\) to \(\text{NO}_3^-\) but will be moderated by the high pH of the effluent (and its origins) and by the potential buffering capacity of the soil.

**Total carbon and nitrogen**

There was a general increase in TC and TN associated with effluent irrigation, but the effect was greatest at Farm 2. This site had a TC content of 22.9% and TN content of 2.44% compared with the non-irrigated sample of 4.75 and 0.39%, respectively, in the surface 100 mm. We attribute the very large TC and TN values to the irrigated soil being maintained as a grazed Kikuyu pasture for >20 years. Increase in TC will tend to confer structural stability on soils that purely physico-chemical considerations suggest should be unstable (Collis-George and Smiles 1963; Rengasamy et al. 1984). This is consistent with the apparently anomalous stability of the irrigated surface soils from Farm 2.

**Concluding remarks**

Conclusions from this survey must be qualitative because farm histories were too inexact to estimate material balances that might identify effects of soil type or climate on profile response to effluent irrigation. Nevertheless, systematic patterns emerge in relation to the effluent and to the consequences of its application to soils.

Effluents from all piggeries are chemically similar, with high pH and high EC, and all effluents have very high values of water-soluble \(\text{NH}_4^+\) and relatively high concentrations of \(\text{K}^+\) compared with \(\text{Na}^+\), \(\text{Ca}^{2+}\), and \(\text{Mg}^{2+}\). Ratios of \(\text{NH}_4^+\) and \(\text{K}^+\) to divalent cations are high. Both of these cations have similar strong affinity for the soil colloid relative to \(\text{Na}^+\), so we expect initially that \(\text{NH}_4^+\) and \(\text{K}^+\) will dominate the exchange complex but \(\text{NH}_4^+\) will then decrease as it is oxidised to \(\text{NO}_3^-\), or taken up by plants. An increase in \(\text{K}^+\) was observed in both the soil saturation extract and the exchangeable cations of irrigated soils when compared with their non-irrigated counterparts. The KAR and EKR seem to be particularly sensitive indicators of irrigation using

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Farm (soil group)</th>
<th>pH (1:5 soil:0.01 M CaCl(_2))</th>
<th>Total C</th>
<th>Total N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Irrigated</td>
<td>Non-irrigated</td>
<td>Irrigated</td>
<td>Non-irrigated</td>
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piggery effluent because of the strong affinity of K⁺ for the exchange complex. Neither the soil nor the extract contained NH₄⁺ at sampling time. Ratios and total concentrations of monovalent and divalent cations in the effluents and the saturation extract of irrigated soils also suggest that these soils will be structurally stable using criteria first defined by Collis-George and Smiles (1963) and data of Quirk and Schofield (1955). However, this conclusion becomes less certain if criteria of Rengasamy et al. (1984) for Red Brown Earth are used, and data presented in Appendix 1 suggest that the effects of all monovalent cations in the soil solution must be considered if a reliable indicator of structural stability based on solution cation ratios and concentrations is to be developed. Basic principles of this approach are discussed.

Because of interactions between the nitrogen oxidation pathways, the high pH of the effluent, and the buffering capacity of the soil, the pH of the soils generally does not appear to respond systematically to irrigation, although the ECₑ of irrigated soils tends to increase, as does the total carbon content.

All effluents are too salty and should be diluted if they are to meet most irrigation guidelines (Anon. 1995; Kruger et al. 1995; Richards 1954). One might wonder whether the measured EC of an effluent with a high concentration of NH₄⁻-N and a high pH is the best basis for assessing its suitability for irrigation or whether a reduced value of EC, based, for example, on the sum of the cations other than NH₄⁺, might be more appropriate. Either way, these ECₑ values remain unacceptable.

Finally it is useful to comment on the experimental procedures we used in this survey. It is easy to identify gaps in data collection in retrospect and costs of analysis demand a parsimonious approach to measurement. At the same time, complementary measurements that test internal consistency of datasets and also permit sound basic comparisons across treatments are most important. The methods described here contain 2 major deficiencies. The first was the failure to ensure that exchangeable cations and those in the saturation extract formed an equilibrium set. The data would then have permitted estimation of selectivity coefficients and thence permitted estimation of selectivity coefficients and thence permitted calculation of the consequences of soil treatments are most important. The methods described here are developed. Basic principles of this approach are discussed.


References


Coagulation (C) of the clay in a 1:5 soil:water suspension. Through the effect of solution ratio and TCC on dispersion (D) or (using the terminology of Rengasamy KAR and SAR, and their sum, MCAR, these experiments relate the potassium and sodium adsorption ratios, Appendix 1

Table A1. Measured equilibrium solution cation concentrations and adsorption ratios presented as averages of the duplicates shown on the graph.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Na</th>
<th>K</th>
<th>Ca (mmol/L)</th>
<th>Mg</th>
<th>TCC</th>
<th>SAR</th>
<th>KAR (mmol/L)</th>
<th>MCAR</th>
<th>D/C</th>
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<td>NI[5:5]</td>
<td>0.082</td>
<td>0.235</td>
<td>0.255</td>
<td>0.157</td>
<td>0.729</td>
<td>0.181</td>
<td>0.518</td>
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<td>NI[4:5]</td>
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<td>0.322</td>
<td>0.535</td>
<td>0.258</td>
<td>1.287</td>
<td>0.273</td>
<td>0.512</td>
<td>0.785</td>
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<tr>
<td>NI[3:5]</td>
<td>0.257</td>
<td>0.412</td>
<td>0.849</td>
<td>0.397</td>
<td>1.915</td>
<td>0.326</td>
<td>0.522</td>
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<td>NI[2:5]</td>
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<td>0.503</td>
<td>1.189</td>
<td>0.551</td>
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<td>0.370</td>
<td>0.539</td>
<td>0.909</td>
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<td>NI[1:5]</td>
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<td>1.438</td>
<td>0.664</td>
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<td>I[5:5]</td>
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<td>2.097</td>
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<td>I[3:5]</td>
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<td>4.981</td>
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<td>0.959</td>
<td>11.574</td>
<td>2.707</td>
<td>3.945</td>
<td>6.657</td>
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Manuscript received 8 May 2003, accepted 25 November 2003
These data form part of a more extensive experimental set so our discussion here is cursory but uses the most stringent of the Rengasamy et al. (1984) stability criteria for topsoils (their eqn 4):

\[
TCC = 1.46SAR + 1.44
\]

Mechanically disturbed topsoils where TCC is less than this equation indicates are said to be stable. Non-irrigated topsoil data (NI data in Table A1) are consistent with this relation insofar as the 1:5 and 2:5 suspensions dispersed and the 4:5 and 5:5 suspensions coagulated (C) and hence bracket this line. Irrigated topsoils (I in Table A1) remained dispersed (D) after 24 h. The use of SAR \(v\) TCC (or KAR \(v\) TCC) in relation to Eqn A1 would have incorrectly implied that these materials would be coagulated. The MCAR \(v\) TCC relation meets the Rengasamy criteria for the NI soils, although the irrigated (I) soils bracket the line but were clearly and stably dispersed.

Subsequently, clay from the irrigated soil was equilibrated with SAR (in the absence of K\(^+\)), KAR (in the absence of Na\(^+\)), or MCAR (= KAR + SAR) values of 4 (mmol/L\(^1/2\)) and a TCC of 20 mmol/L (i.e. their SAR or KAR was comparable with the most concentrated, although still dispersed suspensions of field soils). The clay coagulated in each of these systems. The same clay, with TCC values of 8 mmol/L, tended to coagulate, but when the SAR, KAR, or MCAR values were increased to 8 (mmol/L\(^1/2\)) with TCC remaining at 4 mmol/L, they dispersed. That is, the effects of K\(^+\) and Na\(^+\) in the adsorption ratios on coagulation and dispersion of this clay appear to be additive.

Subsequently, clay from the irrigated soil was equilibrated with SAR (in the absence of K\(^+\)), KAR (in the absence of Na\(^+\)), or MCAR (= KAR + SAR) values of 4 (mmol/L\(^1/2\)) and a TCC of 20 mmol/L (i.e. their SAR or KAR was comparable with the most concentrated, although still dispersed suspensions of field soils). The clay coagulated in each of these systems. The same clay, with TCC values of 8 mmol/L, tended to coagulate, but when the SAR, KAR, or MCAR values were increased to 8 (mmol/L\(^1/2\)) with TCC remaining at 4 mmol/L, they dispersed. That is, the effects of K\(^+\) and Na\(^+\) in the adsorption ratios on coagulation and dispersion of this clay appear to be additive.

These relations require more examination but theoretical reasons are sound for proceeding the way we do (but see the qualifications on the use of criteria such as Eqn A1 discussed by Rengasamy et al. 1984). Note too that Rengasamy et al. (1984) measured, but did not consider, K\(^+\) and give no data, but with samples containing significant amounts of K\(^+\), their structural stability criteria may be more stringent than is appropriate for general application.

Fig. A1. Adsorption ratios for sodium (SAR), potassium (KAR), and the monovalent cation adsorption ratio, MCAR (mmol/L\(^1/2\)), of the soil:water mixes described in the Appendix and graphed vs. their total solution cation concentration, TCC (mmol/L). Rengasamy et al. (1984) derived the curved line in their study of the effect of Na\(^+\) on Australian Red Brown Earths to discriminate between dispersed and coagulated clay suspensions, as discussed in the text.