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AUSTRALIAN
Pork

Better Nutrient Management on Pig Farms:
A guide for interpreting soil and by-product analyses

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Integrity Ag Services
Stephen Wiedemann
36a Highfields Road
Highfields QLD 4352

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Table of Contents

List of Tables

List of Figures

1 Introduction

The Australian pig industry aims to operate in a sustainable manner that minimizes negative impacts and maximizes benefits to the surrounding agricultural land. One of the largest interactions between a piggery and the surrounding land occurs as a result of by-product application. By-products (effluent, spent bedding and solids) can prove beneficial or harmful to soil health and crop or pasture performance, depending mostly on how they are managed. In general, manure and effluent are not balanced fertilisers because the ratio of nutrients doesn't match plant requirements and not all nutrients are available in the first year. Consequently, it is important to understand nutrient and soil analyses to manage nutrient requirements and set rates for additional fertiliser inputs as required. Poorly managed by-product applications can result in negative environmental impacts beyond the borders of the farm, via nutrient losses.

One key aspect to appropriate nutrient management is a clear and accurate understanding of by-product characteristics and soil nutrient status. These are typically assessed via laboratory analysis, but some advisors and regulators have varying levels of skill and knowledge to interpret the results.

This guide provides information on:

- How to understand and interpret manure and effluent analysis results.
- How to understand and interpret soil indicator results in by-product utilisation areas including:
    - General soil indicators,
    - Agronomic soil indicators, and
    - Environmental soil indicators.

There are numerous guides available for interpreting soil tests, but they tend to focus on the minimum amounts of nutrients needed for good soil management. However, because nutrients are often above minimum levels in by-product utilisation areas, this guide focuses on understanding when nutrient or other indicators are too high, and the risks involved for both the environment and good crop and pasture management.

Section 2 gives an overview of how to understand and interpret results for effluent and manure, while Section 3 provides both an overview and also information regarding monitoring and management of soils, which includes how to manage effluent and manure inputs. Good management starts with clear understanding of by-products and soil requirements.

The guide does not replace site-specific assessment or advice, and neither does it cover advice on how, when or where to take samples. For advice on how to take a successful sample including information on timing, soil depths and suggested regularity of testing see the NEGP Appendix D and Section 17/NEGROP Appendix 3 and Section 15) and licence conditions.

Introduction: Key Points:

- Sustainable by-product and soil management is a priority to the Australian pig industry
- Good management starts with understanding by-product characteristics and soil requirements for agronomic and environmental goals

2 Interpreting Manure and Effluent Analysis Results

Manure and effluent can be valuable crop and pasture inputs if managed as fertiliser inputs or soil conditioner. However, the composition of these by-products can vary, and in some instances there can be harmful elements that need to be managed. Good management starts with the right information, and this chapter outlines what is usually contained in manure and effluent, and how to interpret the results. The results are 'general' values and it is recommended to get laboratory tests done on by-products before applying them. Manure is also deposited directly to soil in outdoor pig systems, but these inputs are rarely determined from an analysis of the manure. Instead, calculations can be made from mass balance principles and these are covered in other guidelines.

Interpreting Results - Key Points:

- Manure/effluent can be valuable as crop /pasture inputs/soil conditioner.
- Good management starts with good understanding of:
  - Potential benefits,
  - Nutrient composition,
  - Potential risks.

2.1 Interpreting Effluent Results

Piggery effluent is made up of water, faeces, urine and waste feed flushed from a piggery, and subsequently treated in a range of different treatment systems. The type of treatment system and the stage at which the sample is collected has a substantial impact on the characteristics shown. Samples must be collected at the point in the system just prior to spreading, to provide a representative sample. In conventional uncovered anaerobic ponds, for example, this would typically be from the final, wet-weather pond in the series, and results from the final pond at piggeries in NSW and QLD are shown in Table 1.

Sampling - Key Points:
Samples must be collected from the point **just prior to spreading** to get accurate results.

Table 1 General characteristics and nutrient test results from the final ponds in the treatment systems of piggeries in NSW and QLD

Element	Units	Effluent at work [a]	DEEDI data [b]	
			Average	Range
Dry matter	mg/L	3623	7900	1100-44300
Volatile solids	mg/L	1809	1640	480-5290
pH		8.0	8.0	7.0-8.7
Total nitrogen or TKN	mg/L	(384)	584	158-955
Ammonium nitrogen	mg/L	249	144	25-243
Total phosphorus	mg/L	44	69.7	19.3-173.1
Ortho-phosphorus	mg/L	28.5	16.3	2.4-77.9
Potassium	mg/L	-	491	128-784
Sulphur	mg/L	22 (9-50)	-	-
Sulphate	mg/L	26	47.6	13.3-87.2
Copper	mg/L	-	0.09	0.00-0.28
Iron	mg/L	-	0.56	0.09-1.61
Manganese	mg/L	-	0.02	0.00-0.05
Zinc	mg/L	-	0.47	0.16-1.27
Calcium	mg/L	-	20.6	7.3-41.2
Magnesium	mg/L	-	25.0	6.6-72.3
Sodium	mg/L	603	399	41-1132
Chloride	mg/L	810	19.1	3.6-34.4
Conductivity	dS/m	-	6.4	2.5-11.7

Table Reproduced [1]

DEEDI = Department of Employment, Economic Development & Innovation, QLD

TKN = Total Kjeldahl nitrogen

[a] Samples from piggeries in New South wales, Queensland and Western Australia [2]

[b] Unpublished data [1]– samples from 10 piggeries in southern Queensland

General Characteristics of Effluent

General Characteristics - Key Points:

- Important general characteristics include dry matter levels, VS and pH.
- High VS or acidic effluent can be a sign your treatment system isn't working.

Important general characteristics include total and volatile solids (TS and VS), and pH. Solids content (sometimes measured and reported as 'dry matter' - DM) provides a measure of the handling characteristics of the effluent. High levels of solids (> 10%) make pumping difficult, and indicate poor efficiency in the treatment system, unless the sample is from a desludging event. If solids or dry matter content is reported in mg/L it is helpful to note that 10,000 mg/L is equivalent to 1%. As shown in Table 1, average dry matter is well below 1%. If the influent has a VS:TS ratio of 80%, then you wouldn't want the TS (dry matter) content to exceed 2%. The extreme level shown in the range (DEEDI data, equivalent to 4.4%) suggests the treatment system was not operating. If the pond is functioning well it should be reducing the VS concentration by 70%. The need for desludging should be investigated if the VS reduction in the primary anaerobic pond falls below 50% or the VS concentration of the treated effluent exceeds 1%.

Volatile solids indicate the proportion of total solids made up of organic material. Anaerobic treatment systems are designed to break down VS and consequently, elevated levels are an indication that the system is not operating correctly. When aiming to understand characteristics for pumping and general handling, information regarding the total solids or DM content is sufficient, though knowing the VS content can be helpful for designing and/or understanding the efficiency of treatment systems.

Effluent pH is another important factor. Generally, effluent is alkaline (average pH = 8 – see Table 1) when treatment systems are operating correctly. Acidic effluent (generally defined as a pH < 6), is usually a sign the treatment system has failed, and if this is the case, the ponds are likely to be generating high levels of odour and accumulating sludge rapidly. Effluent pH in the range shown in Table 1 doesn't generally result in negative impacts to soil, as other factors contribute more strongly to soil pH than the initial pH of the effluent.

Salinity and Sodicity

General

Salinity levels are a key indicator of effluent quality and high levels can have a negative impact on soil health. The general electrical conductivity (EC) measure provides an indication of salinity levels, though closer assessment of the drivers of high EC are also recommended to prevent misleading interpretation. Negative salinity impacts are mainly associated with chloride (Cl) and sodium (Na), but other ions (such as potassium) common in effluent also contribute to EC. For this reason, interpreting salinity in effluent needs to focus on chloride, sodium and EC.

Guideline Values and Interpretation

Average EC levels reported for samples collected in Queensland (6.4 dS/m) indicate effluent salinity is very high and suitable only for very tolerant crops [3]. However on closer analysis, average chloride concentrations in the same dataset (19.1 mg/L is classed as very low and would not result in plant toxicity problems, see Table 2 below) [3]. In contrast, some research shows high levels of chloride and may not be suitable for most crops, with the exception of the most tolerant species (Table 2) [2]. Where Cl levels are high, leaf burn may occur and if possible effluent irrigation should be followed with clean water irrigation.

Table 2 Irrigation water quality criteria for salinity based on 90% yield of the plant groupings of Maas and Hoffman [4], assuming 15% leaching faction [details of the derivation of the criteria are provided in 5]

Irrigation water quality (assume LF = 0.15)				
EC (dS/m)[a]	**Chloride (mg/L)**	**Sodium (mg/L)[b]**	**Plant salt-tolerance grouping[a]**	**Affected crop [6, 7]**
< 0.65	< 220[a] (< 178)[b]	< 114	Sensitive	Almond, apricot, citrus, plum, grape
0.65-1.3	220-440[a] (178-355)[b]	114-229	Moderately sensitive	Capsicum, potato, tomato
1.3-2.9	440-800[a] (355-710)[b]	229-458	Moderately tolerant	Barley, maize, Lucerne, sorghum
2.9-5.2	800-1500[a] (> 710)[b]	> 458	Tolerant	Cotton, sugar beet, sunflower
5.2-8.1	1500-2500[a]	nr[c]	Very tolerant crops	nr[c]
> 8.1	> 2500[a]	nr[c]	Generally too saline	nr[c]

[a] Data sourced [3], [b] Data sourced [8], [c] nr – not reported

High EC levels can also be an indication of elevated sodium in effluent. The average sodium levels in Table 1 (603 and 399 mg/L) equate to sodium application rates of 603 and 399 kg/ML applied. This quantity of sodium has the potential to substantially increase soil exchangeable sodium percentages (ESP) when applied at elevated levels.

Management Considerations

Elevated sodium levels in effluent will require monitoring and management in soil (see chapter 3) because this causes damage to soil structure.

High levels of sodium can also impede infiltration, and the Sodium Adsorption Ratio (SAR) can be used to predict this problem. Because SAR is a ratio (sodium relative to calcium and magnesium), levels can be high even where sodium levels are not high and it does not necessarily provide commentary

Salinity and Sodicity - Key Points:

- **Salinity** is important in understanding effluent quality.
- Effluent EC is often high, but **Cl and Na** are better indicators of the negative impacts of salinity for effluent and manure.
- Where Cl and/or Na levels are high, careful management practices must be put in place to avoid soil salinity.

on absolute loading rates. A general relationship for interpreting SAR relative to EC is shown in Figure 1.

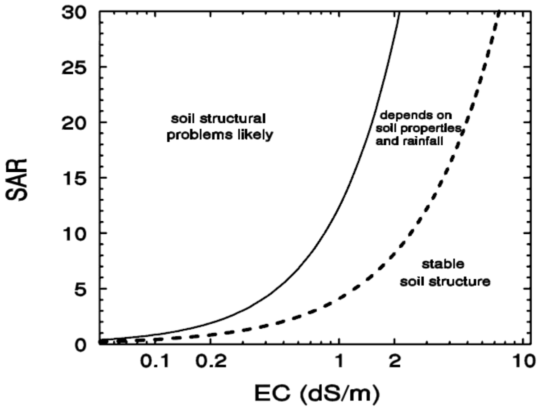

Figure 1 Relationship between SAR and EC of irrigation water for prediction of soil structural stability [6, 9, 10].

Nutrients

General

Effluent contains high levels of macro and micro nutrients which are valuable for pasture or crop production, but can have negative impacts if not well managed. Two factors need to be considered when assessing nutrient levels: i) the total quantity that will be applied at the planned irrigation rate, and ii) the availability of these nutrients for plant uptake or loss.

Guideline Values and Interpretation

Total application rates can be estimated from the concentration of each nutrient and volume of irrigation. A simple rule of thumb is that for every ML applied, the concentration of nutrient in the effluent (in mg/L) is equivalent to the mass of nutrients in kg/ML.

Nutrients - Key Points:

- **IMPORTANT TO CONSIDER:**
  - Total quantity of nutrients to be applied in effluent.
  - Availability of nutrients for uptake, and loss rates when irrigated
- **Rule of thumb:** for every ML applied, the concentration of nutrient in mg/L = mass of nutrients in kg/ML. For example, if effluent contains 40 mg/L of total phosphorus and is applied at 1 ML/ha, the application rate of phosphorus will be 40 kg/ha. This approach provides a good starting point.

The next step is to assess nutrient availability. Nutrient availability is variable and will be different depending on management practices such as application method, and a range of soil and plant factors. Total nutrient levels are the starting point for determining the amount of available nutrients. The proportion that is expected to become available to plants in the first and subsequent season can be determined from both the amount of nutrient in immediately available forms and additional factors.

For nitrogen and phosphorus, it can be useful to test for the rapidly available forms of these nutrients (phosphate and ammonium). Table 1 shows that the ratio of available P (orthophosphate) to total P ranged from 23-65% in the two sample sets, while the ratio of ammonium N to total N ranged from 25-65%. Ortho P and ammonium N can be considered rapidly available for plant growth. However, this shouldn't be thought of as the only available nutrients in effluent or manure. Plants may also take up some nitrogen from organic forms [11], and phosphorus uptake from manures has been found to equal uptake from fertiliser in some situations [12], despite lower apparent available P in the manure samples. Ammonium N levels also give an indication of the amount available for loss via volatilisation to the atmosphere. Loss rates of 25-50% of total N are commonly quoted for irrigated effluent, but losses are lower if effluent is rapidly incorporated [13].

Management Considerations

As a rule of thumb, setting application rates based on the phosphorus, so that the applications of P match plant requirements is a sound approach. This may require additional nitrogen or potassium fertiliser.

Potassium levels can be very high in effluent, and are rarely limiting to plant production when application rates are set to match the amount of phosphorus and nitrogen available. Very high potassium levels (i.e. > 600 mg/L) may induce cation imbalances in soils within effluent irrigation areas and this aspect should be managed by balancing high potassium inputs with high exports in crop products. This is best achieved with hay or silage crops.

N/P/K - Key Points:

- **Rule of thumb:** Set application rates based on the phosphorus plant requirements.
- Calculate nitrogen inputs and supplement with fertiliser as required.
- Potassium levels are often high and can be utilised by growing crops with higher K requirements.

2.2 Spent Litter and Sludge

Piggery spent litter is collected from deep litter piggeries, and is a mixture of urine, faeces and bedding material (commonly straw, sawdust or rice hulls). The characteristics are influenced by the ratio of manure to bedding material and the type of bedding used. Nutrient contents from a broad survey of spent litter are provided in Table 3, and levels of potentially harmful trace metals are shown in Table 4.

Sludge is a solid material collected from the bottom of an anaerobic treatment pond or digester and contains the material that settles from manure during treatment. It has substantially different characteristics compared to spent litter and can contain high levels of some nutrients and trace metals. Typical analyses are shown in Table 5.

Table 3 Nutrient content of spent bedding from deep litter piggeries

		Rice hulls and Straw combined			Straw			Sawdust or Woodchips		
Element	**Unit**	**Ave**	**Max**	**Min**	**Ave**	**Max**	**Min**	**Ave**	**Max**	**Min**
Chloride*	%	0.60	0.80	0.40	0.80	1.30	0.30	0.70	1.10	0.70
Conductivity*	dS/m	9.60	10	9.20	12	15.6	6.60	13	13	13
pH*		7.10	7.30	7.00	6.80	8.50	5.70	6.30	6.30	6.30
Calcium	%	1.56	2.10	0.90	2.63	5.39	0.40	2.34	2.70	2.28
Copper	mg/Kg	167	474	0	172	423	0	<0.05	<0.05	<0.05
Iron	mg/Kg	1196	2032	0.70	4428	9740	0.10	1076	2150	1.10
Magnesium	%	0.50	0.66	0	0.67	1.80	0	0.51	0.70	0.40
Manganese	mg/Kg	282	404	0	362	585	0	145	289	0.30
Phosphorus	%	1.01	1.30	0.60	1.26	2.63	0.20	1.00	1.30	0.99
Ortho-Phosphorus*	%	0.40	0.60	0.30	0.40	0.60	0.20	0.40	0.50	0.40
Potassium	%	1.48	2.10	0.97	2.12	3.84	0.60	1.66	1.90	1.52
Sodium	%	0.36	0.55	0.10	0.69	1.79	0.10	0.34	0.50	0.28
Sulphur	%	0.40	0.50	0.30	0.64	1.00	0.10	0.43	0.50	0.35
Total Nitrogen	%	1.95	2.68	0.10	2.99	4.54	0.20	1.38	1.85	0.90
Ammonium Nitrogen	%	0.30	0.50	0.10	0.50	1.20	0	0.60	1.00	0.60
Zinc	mg/Kg	1526	4289	0.00	1028	2943	0	307	614	0.10
Organic Matter**	%	61	64	58	59	81	40	46	46	46
Moisture#	%	58	68	21	47	74	8.50	24	50	6.40
Bulk Density	t/m3	0.26	0.31	0.22	0.31	0.50	0.11	0.19	0.19	0.19

Table reproduced [1, 14]

** Numbers sourced [1].*

*** This number is sourced from [14], other values are combined from [1] and [14].*

 # Measured on a wet basis, all other percentages reported on a dry basis.

Table 4 Trace metal content of spent bedding from deep litter piggeries

		Rice hulls and Straw			Straw			Sawdust or Woodchips		
Element	**Unit**	**Ave**	**Max**	**Min**	**Ave**	**Max**	**Min**	**Ave**	**Max**	**Min**
Arsenic	µg/Kg	438	484	400	1289	2372	348	716	716	716
Boron	mg/Kg	16	21	12	29	54	12	19	19	19
Cadmium	µg/Kg	110	176	84	266	520	52	596	596	596
Chromium	µg/Kg	2946	4072	1108	9384	22680	1804	3648	3648	3648
Lead	µg/Kg	1782	2144	1352	2943	6424	732	2228	2228	2228
Nickel	mg/Kg	3.73	4.44	2.70	7.48	15	2.13	4.82	4.82	4.82

Table reproduced [14]

Table 5 Characteristics of in situ piggery pond sludge

		DEEDI data [b]	
	Effluent at work [a]	**Average**	**Range**
Dry matter	-	13.1% wet basis	6.9-17.1% wet basis
Volatile solids	-	6.9% wet basis	5.3-9.5% wet basis
pH	7.3	-	-
Carbon	-	28.1%	22.5-37.1%
Total nitrogen or TKN	(2617) mg/L	3.41%	2.84-4.02%
Ammonium nitrogen	1156 mg/L	2582 mg/kg	1472-4422 mg/kg
Total phosphorus	1696 mg/L	4.69%	2.83-5.9%
Ortho-phosphorus	1082 mg/L	-	-
Potassium	-	0.75%	0.27-1.33%
Sulphur	-	1.99%	1.53-3.08%
Copper	25 mg/L	1.02%	3.43-1.82%
Iron	-	1.17%	0.52-2.21%
Manganese	-	1050 mg/kg	786-1389 mg/kg
Zinc	-	3188 mg/kg	2184-3698 mg/kg
Calcium	2210 mg/L	7.08%	4.28-10.4%
Magnesium	-	1.93%	1.0-3.19%
Sodium	108 mg/L	0.52%	0.15-1.40%
Selenium	-	0.59 mg/kg	0.07-2.41 mg/kg
Chloride	232 mg/L	-	-
Conductivity	8.5 dS/m	-	-

Table reproduced [1]

DEEDI = Department of Employment, Economic Development & Innovation, QLD.

TKN = total Kjeldahl nitrogen

[a] Samples from piggeries in New South wales, Queensland and Western Australia [2].

[b] Unpublished data – samples from 10 piggeries in southern Queensland

General Characteristics of Spent Litter and Sludge

General characteristics of note include the level of moisture, organic matter and pH.

- Solid by-products such as spent litter and sludge contain some residual moisture. However, laboratory analyses typically report on a dry basis. Consequently, nutrient levels must be multiplied by the mass of dry matter only (total mass minus residual moisture). Residual moisture dilutes the level of nutrients and increases transport costs.
- Organic matter (or organic carbon) levels are another general characteristic of solids by-products that indicates the amount of material present that will contribute to improving soil carbon levels. High levels of organic matter are beneficial for contributing to soil carbon, but where carbon is high and nitrogen levels are low (measured by the C:N ratio), carbon additions can result in soil nitrogen immobilisation when applied. Typically, nitrogen may be immobilised if the C:N ratios are > 15:1 [15]. Typical C:N ratios in spent bedding (from Table 3) range from 9:1 to 15:1 and are unlikely to result in N immobilisation provided N losses during application are not high.
- pH levels in solids tend to be close to neutral, and the impact on soil pH is likely to be affected more by other factors than the pH of the material applied.

General Characteristics - Key Points:
Important general characteristics include moisture levels (increase transport costs), organic matter (indicates soil carbon levels) and pH.

Salinity

General

Salinity levels are much less of a concern in solid by-products compared to levels found in effluent.

Salinity - Key Points:

- Less of a concern than in effluent.
- Better measured by total sodium mass and chloride, not EC.

Guideline Values and Interpretation

While EC is often high (averages between 8.5 and 13 dS/m - Table 3) this is a poor indicator of likely salinity impacts. Instead, it is better measured by the total mass of sodium and chloride. Levels below 1% will result in low additional salt when applied to land: for example, at an application rate of 10 t/ha of spent bedding (30% moisture, wet basis) the total sodium applied would be in the order of 25-48 kg/ha, and chloride would be 40-56 kg/ha. This would result in a change in soil concentrations of 3.2-7.2 mg/kg in the top 0.6 m of soil. These increases are relatively small compared with critical toxicities and are unlikely to be a concern for many soils.

Management Considerations

If planned application rates are high, and/or soil salinity is already elevated, then sodium and chloride levels should be used to determine safe maximum application rates to minimise the impact of salt loading.

Nutrients

General

Solid by-products contain moderate levels of macro and micro nutrients. As with effluent, the factors to be considered are: i) the total quantity that will be applied at the planned application rate, and ii) the availability of these nutrients for plant uptake or loss.

Nutrients - Key Points:

- STEP 1: Calculate total nutrient application rates from concentration and dry mass applied
- STEP 2: Assess nutrient availability (esp. for N & P).

Guideline Values and Interpretation

The first step is to calculate total nutrient application rates. This can be estimated from the concentration and dry mass of solids to be applied. Nutrient levels are moderate in spent bedding but can be very high in sludge, particularly for P.

The next step is to assess nutrient availability. This is particularly relevant for N and P. The level of available N (predominantly ammonium) and P (ortho-P) provide an indication of nutrient availability. From Table 4 it can be seen that the ratio of available P (ortho-P) to total P ranged from 32-40% for spent litter, while the ratio of ammonium N to total N ranged from 15-43%. Ortho P and ammonium N can be considered rapidly available for plant growth and can therefore be a useful starting point for predicting the contribution of nutrients to meet immediate crop or pasture requirements. More P and N may also mineralise from manure during the first and subsequent years. This is dependent on a range of factors and should be considered as part of nutrient budgeting and soil monitoring.

It should be noted that ammonium N can be easily lost via volatilisation to the atmosphere when by-products are applied. Loss rates of 25-50% of total N may occur when manure is surface applied and allowed to dry out, and this should be taken into account when determining likely amounts of N for crop or pasture growth [14].

Management Considerations

Potassium levels are often substantial in spent bedding because of the straw content, but will be lower if sawdust is the bedding material. Both spent bedding and sludge can be valuable products where potassium is required. In general, most (> 90%) of K can be considered rapidly available to the plant.

Trace Metals

General

Levels of trace metals may be high in spent bedding and sludge. High levels of copper and zinc may be found in spent litter and sludge because they are common feed additives. Copper levels rarely exceed recommended limits in spent bedding, while zinc levels may approach recommended limits in some instances.

Trace Metals - Key Points:

- May be high in spent bedding and sludge.
- May need to be applied at low rates, monitored prior to applying and applied only to low risk crops or pastures.

Guideline Values and Interpretation

Because of the high amount of trace metals in spent bedding and sludge, levels may exceed recommended limits for biosolids [Natural Resource Management Ministerial Council - 16] (see Table 6).

Table 6 Limits for contaminants in compost, soil conditioners and mulches for land application (concentrations in mg/kg)

Contaminant	NRMMC
Arsenic	60
Cadmium	20
Chromium	500-3000
Copper	2500
Lead	420
Nickel	270
Selenium	50
Zinc	2500

Table reproduced [16]

Management Considerations

Spent litter and sludge needs to be managed carefully to control potential trace metal contamination by applying at very low rates and monitoring soil concentrations prior to re-applying sludge. Contaminants such as arsenic, cadmium, chromium, lead and nickel have been found to be below recommended limits [14]. Where high levels are observed, application rates should be low (< 1 t/ha) and applied only to low risk crops or pastures.

3 Interpreting Soil Indicator Results in By-Product Utilisation and Outdoor Production Areas

3.1 General Soil Indicators

Soil tests help producers to make better and more cost-effective decisions. There are a wide variety of tests available but in general a standard agricultural soil test report includes most or all of the following tests:

1) Exchangeable cations (Ca, Mg, K, Na and Al) reported in units and as a percent of total CEC/ECEC
2) Cation Exchange Capacity (CEC/ECEC)
3) Soil pH
4) Organic carbon/matter
5) Electrical Conductivity (Soil salinity- EC)
6) Chloride (Cl^-)
7) Exchangeable Sodium Percentage (ESP) (see 2b)
8) Nitrate-N
9) Ammonium-N
10) Total Nitrogen (N)
11) Available phosphorus - Colwell (Colwell P)
12) Phosphorus buffering index (PBI)
13) Sulphur (S), Calcium (Ca) and Magnesium (Mg)
14) Trace Elements (Zn, Mn, Cu)

Analysis results sometimes include recommendations or added information to assist with interpretation, this varies between laboratories and may only be supplied if requested. See the example soil test below (see the red numbers for references on the test itself), and explanations for interpretation in the following section.

eal Environmental Analysis Laboratory
Southern Cross University

Southern Cross University
PO Box 157 Lismore NSW 2480

T: (02) 6620 3678
F: (02) 6620 3957
E: eal@scu.edu.au
W: scu.edu.au/eal
ABN: 41 995 651 524

ROUTINE AGRICULTURAL SOIL ANALYSIS REPORT

Job No:	XXXX
No of Samples:	3
Date Supplied:	dd, month, yyyy
Supplied by:	Valued Client

						Sample 1	Sample 2	Sample 3				
			Sample ID:			28°49'02.9"S 153°17'57"E	#1 Soil	Good #1	*Heavy Soil*	*Medium Soil*	*Light Soil*	*Sandy Soil*
			Crop:			Environmental	Analysis	Laboratory				
			Client:			..	..	..	*e.g Clay*	*e.g Clay Loam*	*e.g Loam*	*e.g Loamy Sand*
		Method	*Nutrient*		*Units*	*XXXX/1*	*XXXX/2*	*XXXX/3*	*Indicative guidelines only - refer Note 6*			
(11.)	🟨	Colwell	Phosphorus	P	mg/kg	20	47	17	*80*	*50*	*45*	*35*
(8.)	⬜	KCl	Nitrate Nitrogen	N	mg/kg	17	3.3	1.6	*15*	*13*	*10*	*10*
(9.)	⬜		Ammonium Nitrogen			1.5	1.8	4.0	*20*	*18*	*15*	*12*
(13.)	⬜		Sulfur	S		24	10	1.6	*10.0*	*8.0*	*8.0*	*7.0*
(3.)	🟥	1:5 Water	pH		units	7.08	6.46	6.95	*6.5*	*6.5*	*6.3*	*6.3*
(5.)	🟩		Conductivity		dS/m	0.126	0.050	0.038	*0.200*	*0.150*	*0.120*	*0.100*
(4.)	🟫	Calculation	Estimated Organic Matter		% OM	1.6	1.8	2.1	*>5.5*	*>4.5*	*>3.5*	*>2.5*
(1.)	🟦	Ammonium Acetate + Calculations	Calcium	Ca	cmol⁺/Kg	6.51	4.57	4.33	*15.6*	*10.8*	*5.0*	*1.9*
	🟦				mg/kg	1305	916	868	*3125*	*2150*	*1000*	*375*
	🟦		Magnesium	Mg	cmol⁺/Kg	3.45	2.50	1.37	*2.4*	*1.7*	*1.2*	*0.60*
	🟦				mg/kg	419	304	167	*290*	*200*	*145*	*75*
	🟦		Potassium	K	cmol⁺/Kg	0.14	0.17	1.01	*0.60*	*0.50*	*0.40*	*0.30*
	🟦				mg/kg	56	68	395	*235*	*190*	*150*	*100*
	🟦		Sodium	Na	cmol⁺/Kg	0.95	0.19	0.10	*0.3*	*0.26*	*0.22*	*0.11*
	🟦				mg/kg	219	44	22	*69*	*60*	*51*	*25*
	🟦	KCl	Aluminium	Al	cmol⁺/Kg	0.01	0.05	0.01	*0.6*	*5*	*0.5*	*0.2*
	🟦				mg/kg	1	5	1	*54*	*45*	*41*	*14*
	🟦	Acidity Titration	Hydrogen	H⁺	cmol⁺/Kg	0.00	0.12	0.02	*0.6*	*5*	*0.5*	*0.2*
	🟦				mg/kg	0	1	0	*6*	*5*	*5*	*2*
	🟦	Calculation	Effective Cation Exchange Capacity (ECEC)		cmol⁺/Kg	11.07	7.61	6.82	*20*	*14*	*7*	*4*
(2.)	🟦	Base Saturation Calculations	Calcium	Ca	%	61.9	63.2	62.5	*77*	*76*	*69*	*60*
	🟦		Magnesium	Mg		32.8	34.6	19.8	*12*	*12*	*16*	*20*
	🟦		Potassium	K		1.4	2.4	14.6	*3*	*4*	*5*	*8*
	🟩		(7.) Sodium - ESP	Na		9.1	2.7	1.4	*2*	*2*	*3*	*3*
	🟦		Aluminium	Al		0.1	0.7	0.2	*7*	*7*	*7*	*9*
	🟦		Hydrogen	H⁺		0.0	1.6	1.5				
	🟪	Calculation	Calcium / Magnesium Ratio		ratio	2.0	1.9	3.2	*6.4*	*6.3*	*4.3*	*3.0*
(14.)	🟩	DTPA	Zinc	Zn	mg/kg	0.4	1.1	0.6	*6.0*	*5.0*	*4.0*	*3.0*
	🟩		Manganese	Mn		32	29	24	*25*	*22*	*18*	*15*
	🟩		Iron	Fe		93	191	61	*25*	*22*	*18*	*15*
	🟩		Copper	Cu		0.9	1.1	0.7	*2.4*	*2.0*	*1.6*	*1.2*
	🟥	$CaCl_2$	Boron	B	mg/kg	0.32	0.28	0.66	*2.0*	*1.7*	*1.4*	*1.0*
(10.)	⬛	LECO IR Analyser	Total Carbon	C	%	0.93	1.03	1.20	*>3.1*	*>2.6*	*>2.0*	*>1.4*
	⬛		Total Nitrogen	N	%	0.07	0.08	0.10	*>0.30*	*>0.25*	*>0.20*	*>0.15*
	⬜		Basic Texture			Clay Loam	Loam	Loam	..	..	..	..
	⬜		Basic Colour			Brownish	Brownish	Red	..	..	..	..
(6.)	🟩	Calculation	Chloride Estimate		equiv. ppm	77	30	24	..	..	..	..
(12.)	🟧	PBI	Phosphorus Buffer Index		Index	226	31	985	*<15 extremely Low; 15-70 Very Low; 71-140 Low; 141-280 Moderate; 280-840 High; >840 Very High*			

EAL Soil Testing Notes

1. All results presented as a 40°C oven dried weight. Soil sieved and lightly crushed to <2 mm
2. Methods from Rayment and Lyons, 2011. *Soil Chemical Methods*
3. Soluble Salts included in Exchangeable Cations - NO PRE-WASH
4. 'Morgan 1 Extract' adapted from 'Science in Agriculture', 'Non-Toxic Farming' and Lamonte Soil Handbook.
5. Guidelines for phosphorus have been reduced for Australian soils
6. Indicative guidelines are based on 'Albrecht' and 'Reams' concepts
7. Total Acid Extractable Nutrients indicate a store of nutrients
8. Contaminant Guides based on 'Residential with gardens and accessible soil including childrens daycare centres, preschools, primary schools, town houses or villas' (NSW EPA 1998).
9. Information relating to testing colour codes is available on Sheet 2 - "*Understanding you soil results*"

Calculations

1. For conductivity 1 dS/m = 1 mS/cm = 1000 µS/cm
2. 1 cmol⁺/Kg = 1 meq/100g; 1 Lb/Acre = 2 ppm (parts per million); kg/ha = 2.24 x ppm; mg/kg = ppm
3. Conversions for 1 cmol+/Kg = 230 mg/Kg Sodium, 390 mg/Kg Potassium, 122 mg/Kg Magnesium, 200 mg/Kg Ca
4. Organic Matter = %C x 1.75
5. Chloride Estimate = EC x 640 (most likely over-estimate)
6. ECEC = sum of the exchangeable cations cmol⁺/Kg
7. Base saturation calculations = (cation cmol+/Kg) /ECEC x 100
8. Ca / Mg ratio from the exchangeable cmol⁺/Kg results

Quality Checked: Kris Saville
Manager, Agricultural testing division

Exchangeable Cations and Cation Exchange Capacity (CEC)

General

Cation exchange capacity (CEC) is a measure of the soil's capacity to hold and exchange cations, with the major contributors to exchangeable cations usually being: Calcium (Ca), Magnesium (Mg) sodium (Na) and potassium (K). Typically, soils with higher CEC are more fertile, though the level of different cations is also relevant to soil health and should be taken into account in by-product utilisation areas to ensure imbalances don't arise.

Guideline Values and Interpretation

When reported, cations are measured individually and reported as centimoles of positive charge per kg of soil, cmol+/kg or milliequivalents / 100g of soil. Each cation is typically also reported as a percentage of the total level of exchangeable cations in the soil, which is important because the proportions of various cations may be more significant to plant growth than actual levels. For the desirable range of cations see Table 7 [17].

Table 7 A guide to desirable proportions of CEC of different cations for many plants

Cations	Desirable ranges (% of CEC) [18]	Desirable ranges (% CEC) [19]
Calcium	65-80	65-80
Magnesium	10-20	10-20
Potassium	3-8	1-5
Sodium	< 1	0-1
Aluminium	< 1	< 5

Table reproduced [17]

Unlike many agricultural systems, cations can become unbalanced in by-product utilisation areas because the additions of Na, K, and Ca with effluent or manure may be high. The relative level of these cations in manure and effluent (see section 2) is often different to the ideal ratio in soil. Specific imbalances to watch for are elevated Na (leading to sodicity, discussed below) and elevated K, which can also cause soil structural imbalances (discussed below).

Management Considerations

If need be, imbalances can be addressed by using soil conditioners with high levels of calcium such as gypsum, or lime if soils are also acidic. Generally, these products are only economically viable where soil health is clearly in decline, such as where sodicity or acidity is also observed. As CEC is a general soil property, there are no specific monitoring or management requirements.

Soil pH

General

Soil pH is a key measure of the acidity or alkalinity of soil, which in turn influences the availability of many nutrients and potentially toxic metals in soil. The test for pH measures the acidity or alkalinity of the soil on a scale from 0 (most acidic) to 14 (most alkaline), by testing for hydrogen (H+ and hydroxyl (OH^-) ions in a water solution. It needs to be noted whether the pH it tested in water or a 0.01 M $CaCl_2$ solution, as the results are reported differently, but the $CaCl_2$ test is more often used as it is less subject to seasonal and field condition variations. Some soils resist changes to pH because of their capacity for buffering, and this capacity is increased with higher organic content and increased cation exchange capacity (CEC).

Guideline Values and Interpretation

A pH range between 5.5 and 8 is generally suitable for most crops. Nutrient availability in response to pH is described by the classic diagram showing the effect of pH on availability of soil nutrients (Figure 2). Definitions for soil acidity and alkalinity are shown in Table 8.

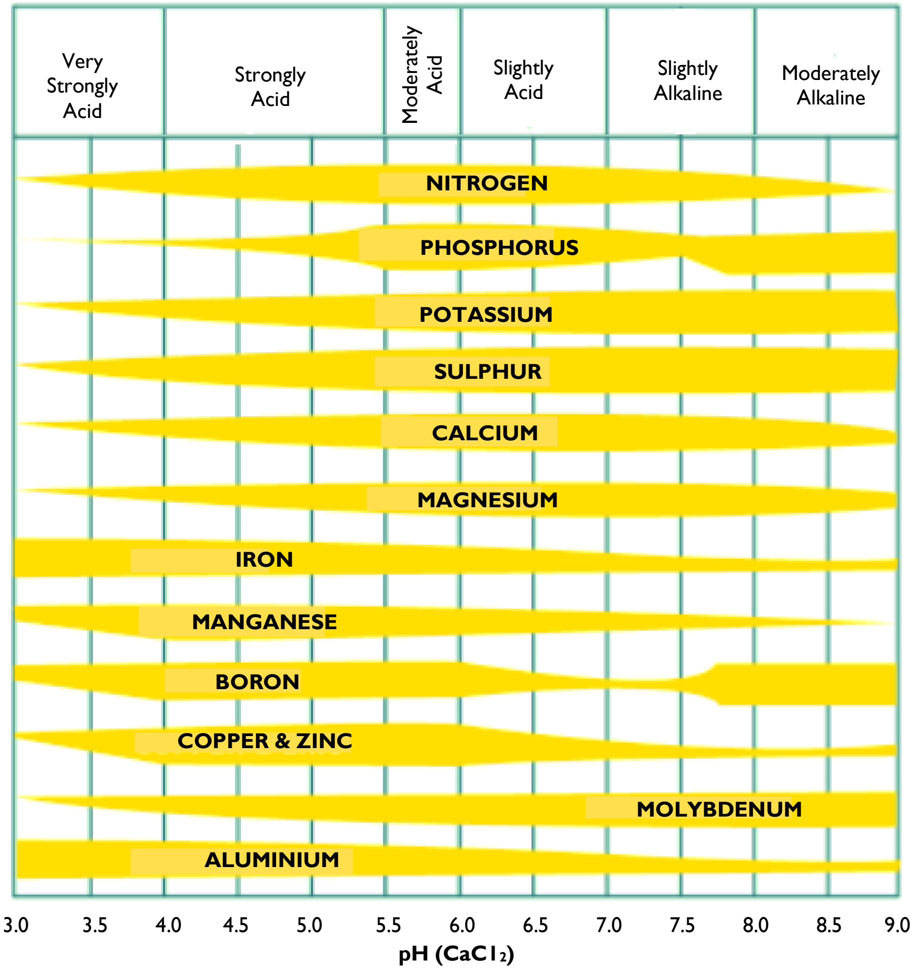

Figure 2 Effect of pH on availability of soil nutrients

Table 8 General interpretation of pH measured in water (1:5 soil:water ratio)

pH$_{water}$	**Ratings**	**Some indications for soil chemistry**	**Occurrence**
< 3.0 3.0 - 4.0	Very strongly acid	Very high levels of acidifying soil organic matter (peats): presence of acid sulfate	Extreme pH for peat soils; disturbed acid sulfate soils
4.0 – 5.0 5.0 – 5.5	Strongly acid*	Acidified soils, Al^{3+} ions in solution	Range in pH for mineral soils in humid regions
5.5 – 6.0	Moderately acid	Range most suitable for plant growth	
6.0 – 7.0	Slightly acid		
7.0 – 8.0	Slightly alkaline		Range in pH common for minerals soils in arid regions
8.0 – 8.5 8.5 – 9.0	Moderately alkaline **		
9.0 – 10.0	Strongly alkaline	Some nutrients becoming unavailable, indications of sodicity, sodium bicarbonate possibly present	Range in pH common for minerals soils in arid regions
10.0 – 11.0	Very strongly alkaline	Extreme pH, high sodicity and carbonates	

Table reproduced [17], previously adapted [20, 21].

* With increasing acidity, exchangeable aluminium increases to toxic levels, cadmium and toxic trace metals become available and molybdenum become increasingly unavailable.

** With increasing alkalinity, test for calcium carbonate (CaCO$_3$). Iron and zinc may be deficient.

Management Considerations

The major soil constraint related to pH is acidification. When soils become more acidic the availability of aluminium (Al) and manganese (MN) rises, and become toxic to crops and pasture plants. Additionally, nutrient availability changes in response to changes in soil pH. In by-product utilisation areas, competing influences may exist that affect pH. For example, some calcium may be present in effluent and manure, which may offset acidification. Conversely, organic acids present in organic matter may slightly acidify soils where by-products are applied regularly. The last and most substantial impact causing acidification is from the nitrogen cycle. Nitrogen added in the ammonium form acidifies soil when it is converted to nitrate, *if nitrate leaching occurs*. For this reason, where nitrate leaching is high because nitrogen is being over-applied, soil acidification usually also occurs. Acidification can also occur where high rates of plant material are removed such as with hay production, because this removes calcium taken up in the hay. As this is a recommended management practice for utilising nutrients in by-product utilisation areas, this can further lead to acidification in these areas.

Monitoring Soil pH:

- Are levels decreasing over time? Are levels below (or approaching) a pH of 5 (Figure 2, Table 8)?

Managing Soil pH:

- Check nitrogen leaching levels – is this contributing to acidity and can this be rectified?
- Check calcium offtake in hay – is this being balanced with inputs or can this be rectified?
- Apply lime at required rates.

Organic Matter

General

Organic matter, in the broadest sense, includes living and non-living organic materials, derived directly from plants and animals, including microfauna and microflora in the soil. It is vital to soil health, and to many physical and chemical processes that occur in soil. Higher organic matter levels promote better soil structure, and can store large amounts of nutrients that are released slowly for plant growth. Improved soil structure aids infiltration and storage of water in the soil profile.

Elevated soil organic matter occurs where organic matter inputs exceed the losses caused by soil respiration or erosion losses. Soils in by-product utilisation areas often have high levels of organic matter compared to comparative production systems where conventional fertilisers are used, for two reasons: organic matter is directly added to the soil via effluent, manure or spent litter, and plant growth is increased because of the higher nutrient additions, resulting in larger amounts of carbon being returned to the soil from plant residues. However, these effects take time to increase soil organic matter levels and are dependent on management and on the level of by-products applied. Management practices such as regular cultivation and regular hay or silage cropping can counteract these affects by accelerating the loss of organic matter or decreasing the level of plant residues returned to the soil.

Guideline Values and Interpretation

Organic matter results are a measure of the percentage of living and non-living organic matter present in the soil. These have been rated and are reproduced in Table 9.

Table 9 The relationship of soil organic matter to soil physical properties

Level of organic matter % (g/100g)	**Level of organic carbon % (g/100g)**	**Rating**	**Interpretation**
< 0.70	< 0.40	Extremely low	Subsoils or severely eroded, degraded surface soils.
0.70-1.00	0.40-0.60	Very low	Very poor structural condition, very low structural stability.
1.00-1.70	0.60-1.00	Low	Poor to moderate structural condition, low to moderate structural stability.
1.70-3.00	1.00-1.80	Moderate	Average structural condition, average structural stability.
3.00-5.50	1.80-3.00	High	Good structural condition, high structural stability.
> 5.15	> 3.00	Very high	Good structural condition, high structural stability and soils probably water repellent.

Table reproduced [17, 22, 23].

Effluent utilisation areas that have long-term, established pastures may have organic matter levels exceeding 5%, though often this will also correspond with elevated nutrient levels and under-utilisation of biomass production. Where cultivation is practiced, this is generally lower, though levels of > 3% have been recorded which is quite good for cultivated Australian cropping soils [17].

Management Considerations

Soil organic matter levels are generally lower than may be expected when solid by-products are applied at sustainable rates to match major nutrient requirements, and levels are strongly influenced by cultivation practices and the amount of crop residue returned to the soil. Where solid by-products are used to build fertility over a number of years, and careful management practices are applied, organic matter levels can be maintained and improved above what would be expected with conventional cropping practices. However, this effect is not consistent in every circumstance [24, 25].

Monitoring OM:

- Are levels increasing/decreasing over time? Are levels at moderate levels or above (Table 9)?

Managing OM:

- If OM levels are very low, review management practices and look for options to increase carbon inputs – stubble retention, zero tillage etc.
- Depending on other factors (N and P levels, salinity) – can manure inputs be increased to provide higher carbon rates?

3.2 Salinity Indicators

Salt levels, or salinity, in soil is a significant issue of concern for agricultural production and can be an environmental concern in by-product utilisation areas. Levels of salinity in soil are generally tested using electrical conductivity (EC), exchangeable sodium percent (ESP) and chloride levels, and these indicators are explained in the sections below.

Electrical conductivity (EC)

General

Electrical conductivity (EC) is a measure of the total level of salts present in the soil solution (soil salinity), and is usually measured in deci-Siemens per meter (dS/m) in a 1:5 soil:water solution. As noted in when discussing interpretation of effluent and manure results, EC is a broad measure, and is influenced by all salts including those that are harmful (sodium, chloride) as well as potassium, calcium, magnesium salts formed with other anions such as sulphates, carbonates and nitrates. As with manure and effluent, soil EC in by-product utilisation areas may be only a partial indicator of salinity, and it is

Monitoring Soil Salinity:

- Test top soil and the bottom of the root zone (0.5-0.6 or deeper depending on the site), are EC levels increasing over time with effluent or manure application?
- Does EC_{se} exceed ‘medium’ salinity ratings (Table 10) in the top soil?
- Are chloride levels > 500mg/kg or above the toxicity level for the crop or pasture being grown?

Managing Soil Salinity:

- This is covered under chloride and sodium sections below.

beneficial to investigate sodium (using the test for exchangeable sodium percent – ESP) and chloride levels.

Guideline Values and Interpretation

It should be noted that many recommendations regarding soil salinity refer to EC values for a saturated extract (EC$_{se}$). This is not the same as the EC$_{1:5}$ values usually given by laboratories. Converting EC$_{1:5}$ values to EC$_{se}$ values for interpretation purposes requires an understanding of soil texture, as this influences the soil moisture holding capacity. Reported conversions may be used (see Table 10 or cited references) [26, 27]. The rating system of the Department of Natural Resources and Mines (DERM) [3] is also useful for interpreting EC$_{1:5}$ results for soils of differing textures.

Table 10 Soil salinity criteria EC$_{se}$ and EC$_{1:5}$ for four ranges of soil clay content

Plant salt-tolerance grouping[1]	**Corresponding EC$_{se}$ range**[2] **(dS/m)**	**Equivalent EC$_{1:5}$ reading, based on clay content of soil (dS/m)**				**Soil salinity rating**
		10-20% clay	**20-40% clay**	**40-60% clay**	**60-80% clay**	
Sensitive crops	< 0.95	< 0.07	< 0.09	< 0.12	< 0.15	Very low
Moderately sensitive crops	0.95-1.9	0.07-0.15	0.09-0.19	0.12-0.24	0.15-0.3	Low
Moderately tolerant crops	1.9-4.5	0.15-0.34	0.19-0.45	0.24-0.56	0.3-0.7	Medium
Tolerant crops	4.5-7.7	0.34-0.63	0.45-0.76	0.56-0.96	0.7-1.18	High
Very tolerant crops	7.7-12.2	0.63-0.93	0.76-1.21	0.96-1.53	1.18-1.87	Very high
Generally too saline for crops	> 12.2	> 0.93	> 1.21	> 1.53	> 1.87	Extreme

Table reproduced [3, 5]

1 - These groupings are statistically derived divisions based on families of linear curves representing the salt-tolerance ratings of the majority of crops [4]. The terminology has been modified and an additional group of sensitive crops incorporated.

2 - EC$_{se}$ at which 10% yield reduction occurs for these plant salt tolerance groups. The EC$_{1:5}$ ranges have been determined from these EC$_{se}$ ranges using the equations provided in the section entitled 'Converting from EC$_{1:5}$ to EC$_{se}$' [page 30 of 3].

Management Considerations

Management of EC is covered in the following sections on chloride and sodium.

Chloride

General

Chloride can be a harmful and even toxic element to plants and inhibits plant growth, causing foliar symptoms such as leaf bronzing and necrotic spots in some species.

Guideline Values and Interpretation

Chloride may not be routinely tested for in agriculture, but because it is present in effluent and manure it is an important test. Chloride toxicity varies between different plant species, with many horticultural species being sensitive to soil Cl levels of < 300 mg/kg. Broad acre crop species are more tolerant, with critical levels in the order of 600 mg/kg (wheat) to 700-800 mg/kg (sorghum and corn respectively – see Table 2). Cotton is more tolerant of chloride toxicity, with critical soil concentrations of 1600 mg/kg. Where chloride levels approach toxic thresholds for the crops grown because of effluent or manure application, yields will decline unless action is taken.

Management Considerations

The best management option is to reduce chloride levels in the effluent, by reducing salt in the diet or in the water used by the piggery. Diet intake can be discussed with the nutritionist. Salt may be high if poor quality ground water is being used, and this could be addressed by treating this water prior to use. Once salt levels are high in the effluent, there are less options to address this problem. If clean water is available, the level and toxicity of the effluent can be reduced by mixing (shandying) the effluent with clean water, or by following up the effluent irrigation runs with clean water irrigation runs. Chloride is highly mobile in the soil profile, and levels will decline because of leaching from the root zone, either by rainfall or clean irrigation water over time provided inputs are ceased or reduced. If levels increase to toxic levels, tolerant crops or pastures can be planted while the area is being rehabilitated.

Monitoring Chloride:

- Check effluent / manure analyses for elevated chloride levels – do they exceed recommended levels for crop or pastures (Table 2)?
- Monitor soil chloride levels. Are levels increasing over time? Are levels approaching/exceeding the thresholds for toxicity (Table 10)?

Managing Chloride Toxicity:

- Check salt levels in diet or intake water – can this be reduced?
- Mix clean water with effluent to reduce chloride levels.
- Irrigate with clean water to manage soil chloride levels.
- Cease effluent irrigation and allow chloride levels in the root zone to decrease.
- Plant more tolerant crop species.

Where irrigation salinity issues are observed, further expertise should be sought to establish a management plan to address the problem.

Exchangeable Sodium Percent (ESP)

General

Sodicity is a specific soil condition caused by elevated sodium, which is commonly measured by the exchangeable sodium percentage (ESP) of the soil. The ESP is the relative amount of sodium ions present in the soil, reported as a percentage of the total level of exchangeable cations in the soil (see explanation in section on CEC above).

Sodium ions attach to the clay in soil, causing it to be more dispersive. Soils are referred to as sodic as ESP increases above the thresholds in Table 11 [3, 28]. Common problems with sodic soils include reduced water availability, susceptibility to wind and water erosion because of soil dispersion, soil surface sealing or crusting, poor infiltration, reduced productivity and increased management requirements [3].

Monitoring Sodicity:

- Check effluent/manure analyses for elevated sodium and/or SAR levels – do they exceed recommended levels for crop or pastures (Table 2)?
- Monitor soil ESP levels. Are levels increasing over time? Are levels approaching or exceeding the thresholds for sodicity (Table 11)?

Managing Soil Sodicity:

- Check salt levels in diet or intake water – can this be reduced?
- Apply gypsum to displace sodium.
- Maintain ground cover to minimise erosion while area is being remediated.

Guideline values and Interpretation

It is important to note that the values given in Table 11 are dependent upon the soil type (e.g. clay soils are less tolerant of ESP levels than sandy soils), and the depths tested (e.g. beyond the strongly sodic level, ESP > 15 can be tolerated if at a subsoil level), and the sodicity tolerance of specific plants grown on the site [3].

Table 11 General criteria for classifying sodicity in soils

Criteria	Description
ESP < 6	Non-sodic
ESP 6-15	Sodic
ESP > 15	Strongly sodic

Table reproduced [28]

It should also be noted that elevated sodium levels are common in in the subsoil of many Australian cropping soils, and subsoil sodicity should be compared with baselines. Because sodic subsoils are not exposed to erosion risks they place lower management constraints than surface soils, though increasing sodicity at depth should be avoided to minimise impacts on ground water quality.

Management Considerations

Where established pastures exist and sodium levels have increased slowly over time, effects may be counterbalanced by high organic matter levels and high nutrient levels.

Where sodicity levels have increased over time in response to effluent or manure application, and exceed sodic thresholds (Table 11) in susceptible surface soils, management practices are recommended to address this.

Sodicity problems are strongly influenced by management. Infiltration can also be maintained where the SAR of the irrigation water is elevated. This can reduce the apparent negative impacts of sodicity in effluent utilisation areas. If declines in infiltration rate are observed, this can be corrected by applying gypsum, or if soil is also acidic, lime may be used. In areas that are regularly cropped, sodicity problems need to be addressed rapidly to minimise the problems of surface sealing, crusting and erosion in surface soil. Gypsum results in displacement of sodium in the soil profile and replacement with calcium. Sodium then leaches from the root zone. Required applications of gypsum may be in the order of 5-7 t/ha [3].

3.3 Macro and Micro Nutrients

Piggery by-products are typically utilised on pig farms or surrounding land as a fertiliser and soil conditioner. Consequently, applications need to be managed to maximise crop or pasture performance, within acceptable environmental limits. This section outlines some agronomic requirements relevant to soils in by-product utilisation areas. Comprehensive agronomic guidance requires site specific information and assessment by trained personnel, and this guide does not seek to provide this type of input. Instead, it highlights particular factors that are important to consider when interpreting soil tests from manure and effluent utilisation areas from an agronomic and environmental perspective.

While agronomic targets focus on maximising production of crops or pastures, environmental targets focus on identifying levels where environmental risks are likely to occur. In contrast to agronomic targets, much less research has been completed on environmental thresholds, and research is also more difficult to conduct because of the number of factors contributing to elevated loss risks, and because of the potentially long pathway and timeframe between nutrient applications to impacts compared to assessment of agronomic targets.

While a large range of factors must be considered for agronomic purposes, the number is considerably smaller for environmental indicators. Two major nutrients are of greatest concern: N (particularly nitrate-N) and P (particularly available P). Salinity is also a concern and threshold levels for salinity are much the same as those used for agronomic purposes. While toxic metals can be a concern, managing input levels for nutrients will generally address concerns with toxicities. One exception is areas where sludge is applied, where specific attention should be given to keeping metal toxicities below critical levels. Specific attention here is directed to the thresholds for nitrate-N and available P.

Nitrogen

General

Nitrogen (N) is a major plant nutrient and is often the most limiting of those required for crops or pastures. At excessive levels, N can also cause elevated environmental risks. In general, manure by-products do not represent balanced sources of nitrogen, and application rates are more appropriately based on phosphorus requirements (or other nutrient or salt contents of the by-product materials) while nitrogen is considered a supplement to other sources.

Nitrogen occurs in the soil in several forms, only some of which are immediately available to plants. Mineralised N (Nitrate – NO_3-, and ammonium – NH_4+) are plant available, though for most plants, N is predominantly taken up in the nitrate form. In addition to testing for nitrate-N, testing for ammonium-N is beneficial, as more ammonium may be present because of effluent or manure applications. Because mineralised forms of nitrogen are highly mobile in soil, samples are best taken at the same time each year for comparative monitoring purposes (for more on sampling strategies, the NEGP Appendix D and Section 17/NEGROP Appendix 3 and Section 15). Tests are best conducted from the surface to the bottom of the observed root zone, as plants will access mineralised N up to the maximum depth of their roots. This may range from 60 cm for some pasture grasses to > 2 m for some cereal crops, where no constraints are present. Expected root depth should be determined by characterising the soil profile and taking into account the crop or pasture type in each paddock or group of paddocks.

In by-product utilisation areas, much higher proportions of soil nitrogen may be present in organic form, either as a result of recently applied manure or effluent, or from long-term soil organic matter build up. Some of these organic N forms are plant available, while others are not.

Mineralisation and plant available organic N supply can be expected to contribute more nitrogen than in systems depleted of organic matter and total nitrogen tests are recommended periodically to develop an understanding of expected mineralisation rates. Alternatively, calculations can be made to take into account potential mineralisation based on the history of manure and effluent applications over the last 3 years.

Guideline Values and Interpretation

Interpretation of total and mineralised N in terms of crop availability is done with reference to expected crop or pastures requirements and requires local agronomic experience. If there is a long history of by-product utilisation on the site, yield may be governed by rainfall or other soil constraints rather than nitrogen.

Management Considerations

Because soils in effluent and solid utilisation areas tend to have higher rates of N mineralisation, an effective management strategy can be to withhold fertiliser early in the season (provided soil N levels are sufficient for early crop growth) then monitor crop growth and plant tissue N levels, applying side dressings of urea if required. In many seasons, no additional fertilisers will be required because of the high levels of mineralisation. For estimated crop requirements based on yield and nutrient removal, see Table 12.

Table 12 Nitrogen and phosphorus removal relative to yield for selected hay and cereal crops

Crop	Yield (t/ha)	N (kg/ha/yr)	P (kg/ha/yr)
Dryland pasture hay	1-4	20 – 80	3 – 12
Irrigated pasture hay	8-20	160 – 400	24 – 60
Lucerne hay	5-15	150 – 450	15 – 45
Dry land winter cereal (grain only)	2-4	40 – 80	6 – 20
Dry land winter cereal (grain + straw)	2-4 grain (+2-5 t straw)	59 – 239	9 – 20
Grain sorghum	2-8	40 – 160	6 – 24
Forage sorghum	10-20	200 – 400	30 – 60

Calculations based on data [29].

The largest environmental risk related to nitrogen management is associated with nitrate leaching below the root zone, where it may enter ground water. Nitrate-N can become toxic when high levels are present in groundwater, which can be caused by excessive use of fertilisers and applications of effluent or manure. Table 13 provides levels for monitoring nitrate N at the bottom of the root zone, which is used as a means of checking that excessive leaching is not occurring. If levels substantially exceed Table 13, management actions are recommended to minimise losses.

Table 13 Nitrate Nitrogen concentrations corresponding to a soil solution nitrate-nitrogen concentration of 10 mg/L at field capacity

Soil Texture	Soil gravimetric moisture content at field capacity (g water/g soil)	Limiting soil nitrate-nitrogen concentration (mg NO_3N/kg soil)
Sand	0.12	1.2
Sandy-loam	0.15	1.5
Loam	0.17	1.7
Clay-loam	0.20	2.0
Light Clay	0.25	2.5
Medium Clay	0.35	3.5
Self-Mulching Clay	0.45	4.5

Table reproduced [30]

Table 14 Summary of recommendations for nitrogen assessment in utilisation areas

Test	Recommendation	Depths	Benefit	Limitations
Nitrate N	Required	Surface to bottom of root zone.	Benchmark test: tests the form of N most available to plants.	Highly mobile and can be lost from soil profile if drainage levels are high. If no other test is used, contributions from ammonium and organic-N must be estimated to determine total profile nitrate-N levels.
Ammonium N	Recommended	Surface to bottom of root zone.	Tests readily available N that can be present in moderate-high levels in by-product utilisation areas.	Shouldn't be used without testing Nitrate-N. Only measures in-situ ammonium at the point of testing. Summed with nitrate-N provides an underestimate of the minimum N available. It is an added cost.
Total Nitrogen	Optional unless required by licence. Recommended when there is no site history of manure/effluent applications to inform management.	0-10 or 0-30 cm.	Shows the total pool of N available for mineralisation.	Does not provide information about mineralisation rate. It is an added cost.

Monitoring and Managing Soil Nitrogen

Soil nitrogen recommendations require more information than a simple target value. The following steps are required:

1. Determine soil root zone N (nitrate-N + ammonium-N) at time of sampling – i.e. before sowing. This requires converting nutrient concentration to mass, using the depth of soil and bulk density.
2. Estimate likely minimum nitrate supply through the root zone, based on the profile of mineral N – will it meet crop requirements through the growing season?
3. Estimate likely mineralisation, based on previous crop yield, organic matter levels, total N levels and previous manure and effluent applications.
4. Estimate total N supply from soil.
5. Estimate expected crop requirements, based on yield and nutrient removal (see Table 12).
6. Set effluent, manure or fertiliser rates based on requirements to meet yield targets.
7. Monitor nitrate levels at the bottom of the root zone at the same location and time of the year (Table 13). If excess levels are observed, review steps 1-6 and aim to match applications with crop requirements more closely in the following year.

Phosphorus

General

Phosphorus (P) is an essential plant nutrient, and is deficient in many Australian soils. However, in by-product utilisation areas where manure P has been applied in excess of agronomic requirements, it can lead to environmental risks. Guidance is provided here to assist with interpretation of P levels in by-product utilisation areas. The guidance cannot replace site-specific assessment, and does not cover general guidance regarding P dynamics in soil.

Excess phosphorus, particularly in inland waterways, is a major contributor to declining water quality globally. The relationship between phosphorus application rates, soil P levels and environmental risk is complicated and varies in response to a range of climate, soil, landscape and management factors. Transport of P from agricultural catchments depends to a large extent upon the coincidence of source (soil, crop, and management) and transport factors (runoff, erosion, and proximity to water course or body) [31]. Because the loss pathways are typically via dissolution in runoff or erosion with soil particles, it is typically surface soil (0-10 cm or shallower) P levels that are of greatest relevance for evaluating environmental risks. Soil P levels also tend to be highest in the soil surface because P can bind strongly to soil particles.

Phosphorus requirements are based on multiple factors including the crop type, time since previous phosphorus application, and sorption capacity of the soil. Phosphorus sorption (reactivity) relates to the capacity of the soil to immobilise phosphorus. Two tests are required to understand soil P availability in soil: a measure of the soil's sorption capacity (one example being the phosphorus buffering index – PBI) and available P. There are numerous tests for available P in Australia, with the most popular being the Colwell P test and the Olsen P test. In some instances, other tests may be used but Colwell P is recommended as the benchmark for agronomic and environmental guidance in most regions. Different target levels exist for each test and for different crops and pastures. As phosphorus availability is very responsive to soil pH modification, pH management should be part of the standard approach to phosphorus management.

In simple terms, the phosphorus buffering index (PBI) measures the extent to which a particular soil type can adsorb P that is applied to it. The higher the PBI value to more ability the soil has to adsorb (fix) the applied P [32]. For effluent and manure application areas, soils with a high P sorption capacity can store phosphorus with lower risks of losses in runoff or via leaching.

Guideline Values and Interpretation

The Colwell P and Olsen P tests differ in how much soil-bound fixed P is released because of the way the tests are conducted. This means that the Colwell P test must be interpreted with the PBI test, whereas the Olsen P test can be interpreted alone, and does not need to be interpreted with differentiation for soil texture, PBI, state or even region. To achieve 95% of maximum pasture production, a critical Olsen P test value of 15 mg P/kg is required [33].

To interpret Colwell P levels, they must be based on a relative value of PBI, as the critical value of Colwell P required increases as the PBI increases (see Figure 3). To target levels for pastures using the Colwell P test, relative to phosphorous buffering index (PBI) [33, 34], use the following figure to determine the potential for maximum pasture growth.

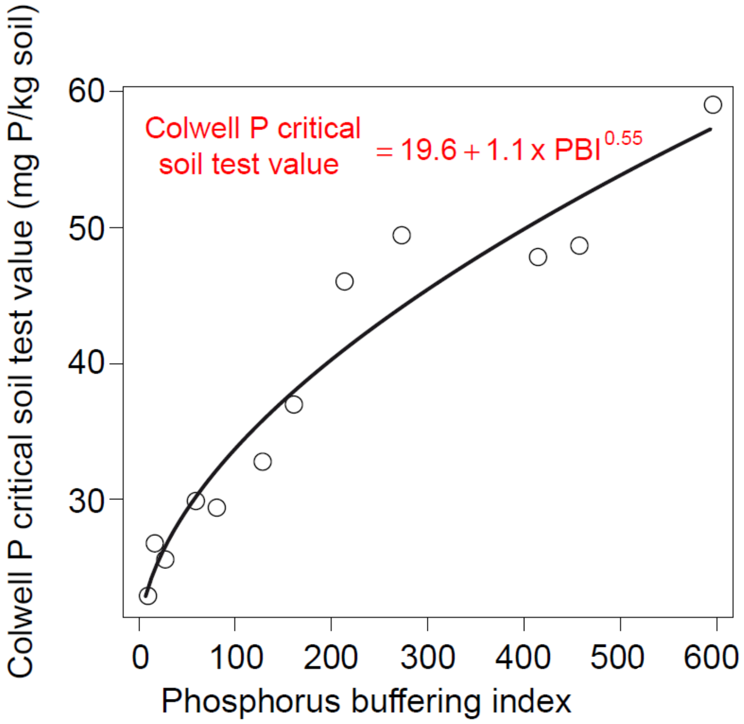

Figure 3 The relationship between critical Colwell P value and soil P buffering index [34]. The critical Colwell P value is the soil test value predicted to product 95% of maximum pasture yield. Table reproduced [33].

The following target levels (Table 15) have been established for a range of crops by Moody & Boland [32], relative to soil P sorption capacity. As can be seen, cereal and vegetable crops have higher requirements.

Table 15 Generalised interpretation guidelines for Colwell-extractable phosphorus (0-10 cm)

Soil P status	**Soil P sorption category**	**Crop P demand**		
		Low (e.g. dryland pasture)	**Moderate (e.g. grain crops)**	**High (e.g. vegetable crops)**
Low	Low	< 10	< 15	< 20
	Moderate to high	< 20	< 30	< 50
Medium	Low	10-30	15-45	20-60
	Moderate to high	20-60	30-90	50-150
High	Low	> 30	> 45	> 60
	Moderate to high	> 60	> 90	> 150

Table reproduced [32]

Management Considerations

When utilising effluent and solid by-products, the placement of P must also be considered. For example, where manure is surface applied and not incorporated, the P will remain near the soil surface. In dryland and zero-till conditions, this may cause localised P deficiencies in crops. In the short term, applying starter fertiliser at half the normal rate may assist crop establishment [14]. In the longer term, building soil P to a moderate level above critical requirements and maintaining soil P through ongoing applications, matched to crop requirements, will reduce the requirement for additional P fertiliser. Recommendations are summarised in Table 16.

Table 16 Summary of recommendations for phosphorus assessment in utilisation areas

Test	**Recommendation**	**Depths**	**Benefit**	**Limitations**
Colwell P *	Required. Interpreted using Table 15 and Figure 3.	Surface (0-10 cm) Usually also tested deeper in the root zone also but less important.	Benchmark test: tests plant available P.	P is immobile and may be located in the surface 2 cm or throughout the top 10 cm, which can alter plant availability particularly in dry conditions. Paddock history should be taken into account to consider likely profile effects.
Phosphorus Buffering Index (PBI)	Required. Interpreted in the following classes: Low = < 35 Medium = 35 - 140 High = 140 - 280 Very high = > 280	Surface (0-10 cm).	Determines the ability of soil to buffer changes in P (mineralisation or sorption).	It is an added cost.
Total Phosphorus	Optional unless required by licence. Consider using when there is no site history of manure/effluent applications to inform management.	0-10 or 0-30 cm.	Shows the total pool of P available for mineralisation.	Does not provide information about mineralisation rate. It is an added cost. Insoluble mineral forms of P measured by this technique may be very poorly available. Added P in manure by products may change total P little – and measurement resolution will be very poor.
Olsen P	May be tested in addition to Colwell P to aid local interpretation	0-10cm	Tests for measurable plant available P.	Most commonly used in Victoria and Tasmania, not commonly used in other states.

Monitoring and Managing Soil Phosphorus:

- Test soil P levels and PBI (Table 16) and interpret using Table 15 – are levels sufficient for crop/pasture production without additional P inputs or are P fertilisers required?
- Review soil P levels for environmental risk – are surface soil P levels > 50% above requirements and plant needs? Are soil P levels increasing annually? Consider reducing application rates and managing paddocks to decrease P levels by maximising crop yield and offtake.
- If soil P levels appear sufficient and the paddock is cropped, check responsiveness to P fertiliser/manure/effluent using test strips.
- Estimate expected crop requirements, based on yield and nutrient removal (for details see Table 12).
- Set effluent, manure or fertiliser rates based on requirements to meet yield targets – P levels in manure will need to be higher in no-till farming situations and fertiliser may still be needed.
- Monitor soil P levels in the surface soil at the same location and time of the year. If excess levels are observed, review steps 1-4 and aim to match applications with crop requirements more closely in the following year.

Potassium

General

Potassium is required in high amounts for crop and pasture production. In Australian soils, potassium is not generally the first limiting nutrient, but deficiencies can occur in some soil types and cropping systems. For example, hay and silage production removes large amounts of potassium which can rapidly lead to deficiencies. Potassium is not generally considered an environmental risk, though large imbalances can cause problems for soil health and for grazing animals and this needs to be monitored.

Guideline Values and Interpretation

There are two sources of potassium (K) that are available to plants in the soil, exchangeable K (available immediately) and non-exchangeable available potassium (NEAP – slowly available). The growth of plants is limited between level of about 0.2-0.5 cmol(+)/kg (or 80-200 mg/kg) [35]. It is also important that testing takes into account the texture of the soil, as pasture response to K declines as clay content increases [33]. Critical levels of potassium for cereal crop production are ideally > 0.25 cmol(+)/kg [35].

Management Considerations

The critical levels reported above are regularly exceeded in effluent irrigation areas, unless high yielding hay or silage crops are regularly grown and removed. Applying effluent or manure is a good strategy for rectifying potassium deficiencies.

Very high concentrations of exchangeable K can cause a cation imbalance, leading to dispersion and soil structural decline. Additionally, elevated exchangeable K levels, at a ratio of K/Ca+Mg) = > 0.07 [36, 37], can cause cation imbalances causing hypo-magnesia (grass tetany).

Monitoring and Managing Soil Potassium:

- Test soil and compare to minimum requirements – if levels are low and environmental risks from N, P and salinity are also low, consider higher rates of effluent or manure.
- If soil test levels are high, aim to maximise yield and crop/pasture offtake in hay or silage.
- Monitor levels in the soil profile at the same location and time of the year. If excess levels are observed, review steps 1 and 2 and aim to match applications with crop requirements more closely in the following year, and/or limit grazing to minimise the risk of grass tetany (Ratio K/Ca+Mg) = > 0.07).

Sulphur, Calcium, Magnesium

General

Sulphur, calcium and magnesium are all required in reasonably large quantities for plant growth and may be deficient in specific circumstances, though acute deficiencies are less common in Australia. Repeated use of solids or effluent will act to reduce deficiencies, as a small amount of each nutrient is added with each application.

Guideline Values and Interpretation

Sulphur deficiencies have been identified in some parts of Australia. Critical values for pastures are 3 mg/kg (CPC S soil test) and 8 mg/kg (KCl-40 S soil test) [33, 37]. Critical levels of 10-12 mg/kg are indicated for Lucerne [38]. Fewer data are available for crop species, but Lewis (1999) indicates critical levels of 8 and 10 mg/kg for corn and cotton respectively.

Absolute calcium and magnesium deficiencies are less common in Australian soils though both can occur, particularly in acidic soils. To interpret them accurately the following need to be considered:

- Absolute calcium levels are ideally above 5 cmol(+)/kg and deficiencies can occur below 0.7 cmol(+)/kg [39].
- Magnesium levels are ideally above 3 cmol(+)/kg, and deficiencies have been observed at concentrations < 0.3 cmol(+)/kg [40].

- Assessment is commonly via review of the proportion of calcium and magnesium relative to total cations. There is disagreement regarding the importance of these proportions, with some indicating ideal ranges of 65-80% for calcium and 10-20% for magnesium [sourced from Agriculture Victoria, 2011, 17], while others suggest the ratio can be much wider without affecting plant growth [40, 41].
- Some advisors strongly advocate a Ca:Mg ratio in the range of 4-6 but this is not strongly supported by research [40, 41] and is not recommended here.

Management Considerations

Because of the relatively high additions of potassium with effluent and manure, levels should be monitored in grazing situations and can be rectified by ceasing effluent irrigation or rectifying calcium and magnesium deficiencies with soil amendments such as lime, gypsum or dolomite additions. The figure below (Figure 4) shows the relationship between maximum pasture yield response when measured against sulphur levels. The choice of amendment will depend on whether other issues such as acidification, sodicity or sulphur deficiencies also exist. Calcium deficiencies tend to occur in acidic and highly leached soils.

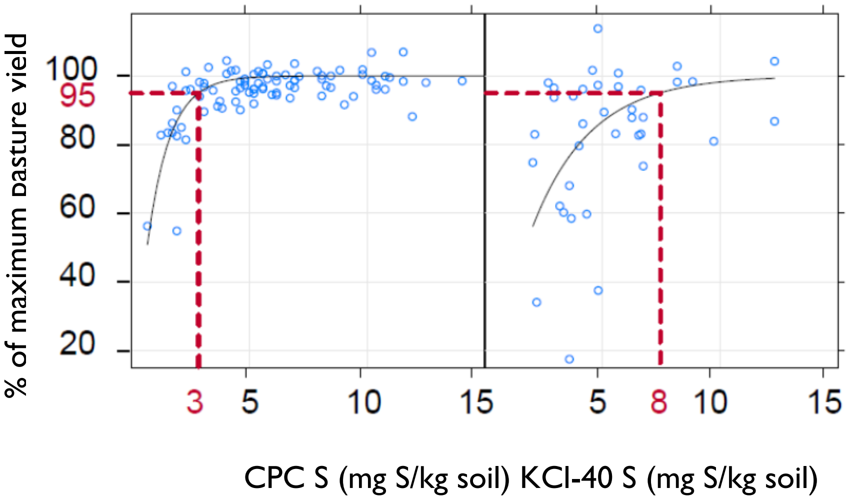

Figure 4 Soil sulphur levels measured by two tests (CPC S, CKI-40 and pasture yield responses. Table reproduced [33].

Monitoring and Managing Soil Sulphur:

- Test soil and compare to minimum requirements – if levels are low and environmental risks from N, P and salinity are also low, consider higher rates of effluent or manure, or apply sulphur based fertilisers or soil conditioners.
- If soil test levels are high, aim to maximise yield and crop/pasture offtake in hay or silage.
- Monitor levels in the soil profile at the same location and time of the year. Rectify deficiencies. Excess levels are not generally a concern with sulphur.

Monitoring and Managing Soil Calcium and Magnesium:

- Test soil and compare to minimum requirements – if levels are low and/or other issues such as acidity or sodicity exist, apply soil conditioners to rectify. Use test strips to evaluate the effectiveness of soil conditioners before large investments to check the benefit/cost ratio.
- Monitor levels in the soil profile at the same location and time of the year. Rectify deficiencies. Excess levels are not generally a concern with calcium and magnesium.

Trace Metals and Micro-Nutrients

General

Micro-nutrients are essential for plant growth and function, and can influence uptake of major nutrients such as phosphorus. While essential for plant growth, plants use these nutrients in much lower quantities than the major nutrients. The following micro-nutrients are required for plant growth: boron, chlorine, manganese, iron, zinc, copper, molybdenum, nickel. Other metals are beneficial at trace concentrations, but at greater concentrations become toxic (e.g. Cu, Zn, and Ni).

Manganese, zinc, boron, copper and molybdenum are deficient in some Australian agricultural soils. But unlike areas where only synthetic fertilisers are used, micro nutrients are rarely deficient in by-product utilisation areas after several applications of effluent or manure have occurred. This is because effluent and manure sources contain reasonable levels of micro-nutrients (see section 2). Critical levels are provided in the following paragraphs.

Guideline Values and Interpretation

Deficiencies of copper can occur below a range of 0.3-2 mg/kg depending on crop and soil conditions [42]. And copper toxicities have occurred in some instances where levels exceeded 150 mg/kg [42].

Critical zinc levels occur in the range 0.2-0.5 ($pH < 7$) and 0.3-0.8 mg/kg ($pH > 7$) with specific levels dependant on crops and pastures [43]. Deficiencies are unlikely to occur where effluent and solid by-products are used. Zinc toxicity should be investigated if levels are well above 4 mg/kg which is the highest recommended requirement for intensive cropping.

Manganese can also be deficient or toxic in Australian soils. In effluent or solids utilisation areas deficiencies are less common because manganese is contained in the by-products applied. Toxicities can exist where pH is low, and may be exacerbated by effluent and solid by-product applications. Toxicity levels vary widely between different plant species. Most crop and pasture species are tolerant of high levels, though Lucerne and canola (observed at levels > 20 mg/kg [44]) are susceptible [44]. This should be monitored in effluent and manure application areas and tolerant crops favoured if levels increase. Further information is available [44].

Boron deficiencies have been identified in some crops scattered in different regions of Australia, and toxicities have also been observed in southern regions. Deficiencies of Boron, though rare in Australia, occur at levels of 0.15 – 0.5mg B/kg soil [45]. Toxicities have been observed in Barley at levels > 3 mg/kg in the surface soil and > 18.8 mg/kg at 20-30 cm [45]. Where large tonnages of material are removed, B deficiencies will occur more rapidly in response to plant removal. As effluent and by-product solids contain boron, crop requirements should be more than adequately provided for and toxicities need to be monitored, particularly where pH is between 5 and 7, or > 8.5.

A range of other micro nutrient requirements exist that may be deficient in some specific instances, and may also induce toxicity when levels are very high. Chloride levels are likely to be high in effluent and manure application areas (see salinity section 3.2) and deficiencies of iron, molybdenum and nickel are expected to be site specific.

Some metals, such as cadmium, chromium, arsenic and lead, perform no beneficial biological function in crops and agricultural livestock and have toxic effects. These are often referred to as harmful or toxic trace metals, but are generally not a problem provided soils are not contaminated from other activities.

Management Considerations

Applying effluent and solid by-products are expected to rectify minor deficiencies without excessive levels accumulating, though this should be monitored as part of regular soil testing. Where sludge is applied, baseline monitoring should be used to check for excessive increases in these nutrients, and care should be taken to avoid large applications of sludge which could result in elevated copper levels exceeding plant toxicity thresholds.

The risk of contamination by harmful trace metals should be managed by applying effluent and solids at levels appropriate for crop and pasture production. Potentially toxic metal inputs should be carefully controlled in inputs, and subsequently monitored in waste streams, and sludge and sludge application areas to ensure they remain below critical levels. These critical levels are provided in table Table 6. It must be recognised that soil contamination with toxic levels of some trace metals may be a difficult, extremely expensive, or impossible to alleviate and therefore prevention is the best option

Monitoring and Managing Micro Nutrients and Trace Metals:

- Review manure and effluent analysis results to check if levels are high relative to Table 6. If high levels are observed, limit applications to low levels, rotate paddocks and monitor soil levels.
- Test soil and compare to minimum requirements and toxicity levels. if levels are low and environmental risks from N, P and salinity are also low, consider higher rates of effluent or manure, or use fertilisers with increased levels of the micro-nutrient required. Critical levels are provided in Table 6
- If toxicities occur, review manure and effluent analysis results and cease applications. Review crop toxicity concerns and consult an expert to establish a plan to rectify the problem.

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