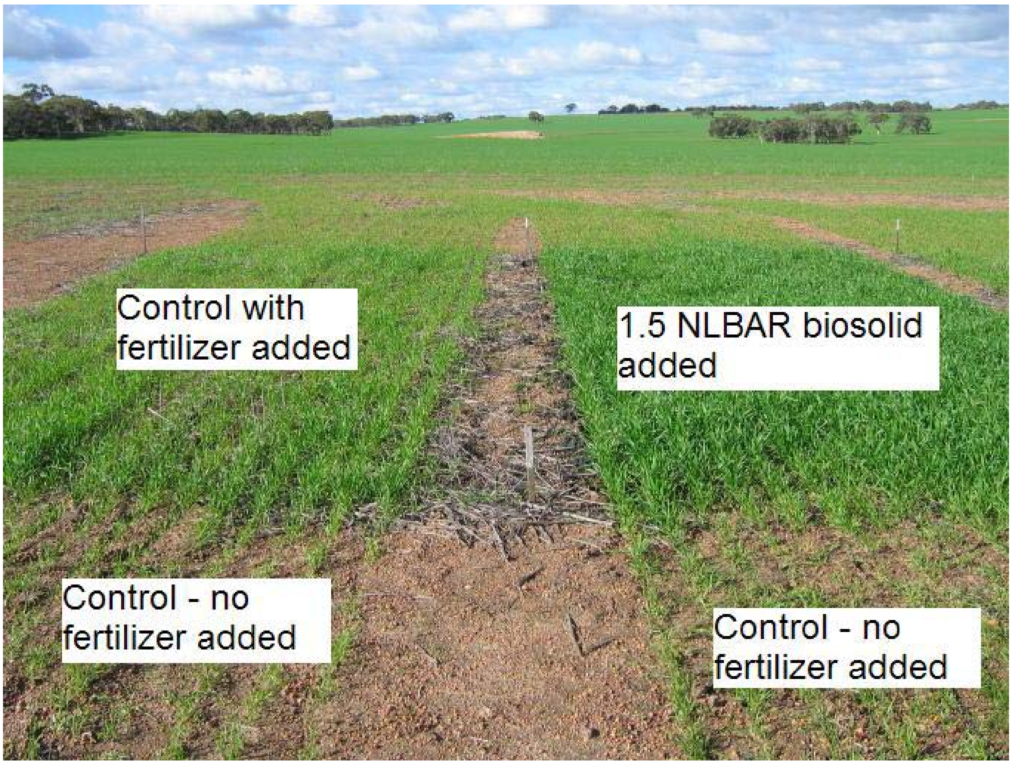
Draft Position Paper
Recommendations of the Australian National Biosolids Research Program on Biosolids Guidelines



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Executive Summary

The Australian National Biosolids Research Program (NBRP) was established in 2002 due to concerns about the relevance of overseas research findings to the Australian situation regarding the land application of biosolids. The NBRP was a large collaborative research program conducted by seven research agencies around Australia that received extensive financial support from several metropolitan and regional water authorities and from several state environmental and natural resource management agencies. The NBRP examined both the potential beneficial and deleterious impacts associated with the land application of biosolids. For this Position Paper all the data from the various state-based trials have been collated to develop recommendations at a national level. Only those results related to deriving new biosolids quality guidelines for metal contaminants and those related to environmental impacts associated with nutrients will be presented in this Position Paper. Findings related to the agronomic benefit of the land application of biosolids have been presented in the various State reports. The NBRP is one of the largest single studies undertaken to examine the potential benefits and deleterious impacts associated with metal contaminants in the land application of biosolids. We are therefore in the unique situation of having a very thorough scientific basis for making recommendations.

A preliminary hazard assessment was conducted which identified that the metals that posed the greatest hazard were cadmium, copper and zinc. The risks posed by these metals in biosolids were assessed and compared to those posed by the same metals in soluble salt form. This was done in order to determine the relative biological availability (i.e. bioavailability) of the metals from biosolids and from the metals salts – which would be used to derive the guidelines for metals in biosolids amended soils. The endpoints evaluated were food quality (i.e. grain cadmium concentrations), crop production (i.e. toxicity of copper and zinc to agricultural crop species) and soil health (i.e. toxicity of copper and zinc to key soil microbial processes - respiration and nitrification).

Critical soil concentrations of copper and zinc that adversely affected microbial processes and plant productivity across all NBRP sites were determined. These were affected by soil properties such as pH, clay content, organic carbon content and cation exchange capacity. A set of soil specific maximum limits for copper and zinc in soils that have received biosolids were derived. These recommended limits state the amount of copper or zinc that can be added to a soil. In acidic, low carbon soils (pH 5,

OC 1%) the recommended limit is 25 mg/kg added copper, which increases to 245 mg/kg added copper in alkaline soils (pH 8) irrespective of the organic carbon content. The recommended limits are, depending on the soil properties at a site, considerably smaller to considerably larger than the current limits of 100 – 200 mg/kg total copper. In acidic, low cation exchange capacity (CEC) soils (pH 5, CEC 3 $cmol_c$/kg) the recommended limit for zinc in soils that have received biosolids is 20 mg/kg added zinc, which increases to 300 mg/kg added zinc when the soil pH is greater than or equal to 7.5 irrespective of the cation exchange capacity. Thus, the recommended limits can be considerably lower to marginally higher than the current limits of 200 – 250 mg/kg total zinc, depending on the properties of the soils at sites.

Critical soil concentrations of cadmium that would lead to exceedance of the Food Standards Australian New Zealand (FSANZ) standard (0.1 mg/kg) for human consumption were determined across all NBRP sites. The critical values were affected by soil properties, principally soil pH and clay content. A set of recommended soil specific maximum cadmium concentrations in soils that have received biosolids were developed. The recommended limit for total cadmium at a soil pH of 5.5 is 0.6 mg/kg in sandy soils (5% clay or less). In alkaline (pH 7.5 or greater) and clayey soils (25% or greater) the recommended limit for total cadmium in soil is approximately 1 mg/kg or greater. Thus depending on the soil properties at a site the recommended cadmium soil concentration is considerably smaller to considerably greater than the value of 1 mg/kg previously recommended by the National Cadmium Management Committee.

From the above recommended limits for cadmium, copper and zinc it is apparent that soils that are acidic combined with either low organic carbon, low clay content or low cation exchange capacity have low critical soil metal concentrations. The critical soil concentrations increased as the pH, organic carbon content, clay content or cation exchange capacity of soils increased.

Based on the recommended soil limits, typical metal concentrations in biosolids and current land application practices example masses of biosolids that could be applied cumulatively to land were calculated. For high risk sites as little as 40 to 90 tonnes in total may be added, while at low risk sites between 280 and 970 tonnes in total may be applied. At typical current agronomic application rates of 10 t/ha this translates to 4 to 98 applications.

The recommended soil limits suggest that the land application of biosolids can remain a sustainable industry which has significant agronomic benefits while protecting environmental and human health. They also suggest that sites that receive biosolids should be carefully selected based on their soil properties.

It is recommended that where sustained repeat applications of biosolids are practiced that soil concentrations of cadmium copper and zinc, and produce cadmium concentrations, be monitored regularly to ensure crop production or quality is not compromised. This is particularly important in sandy acidic soils.

Nutrients were not the principal focus of the NBRP, but despite this some important findings were made and preliminary recommendations can be derived. In warm, sub-tropical Queensland the rate of conversion of organic nitrogen to mineral nitrogen (i.e. ammonia and nitrate) is much more rapid than is accounted for in the current biosolids guidelines. This leads to the accumulation of mineral N in soils at concentrations exceeding crop requirements thus significantly increasing the risk of the off-site migration of the mineral N, and increasing the risk of soil acidification.

If biosolids application rates are restricted to meet crops nitrogen requirements using the nitrogen limiting biosolids application rate (NLBAR), the concentrations of phosphorus in soils amended with biosolids will exceed the plants phosphorus needs, thus increasing the risk of off-site migration. For both nitrogen and phosphorus it is recommended that a national approach such as that of the NBRP be adopted to improve current biosolids guidelines.

Introduction

Australia generally has nutrient-deficient soils and Australian agriculture relies on the continued use of macro- and micro-nutrient fertilisers to replace nutrients removed from the land in harvested produce, lost via surface run-off or leaching or being bound to soil particles and made unavailable.

Recycling and use of nutrients and organic matter contained in metropolitan wastewater biosolids in agriculture makes good sense from both an environmental and economic viewpoint. These materials contain organic matter and nutrients that can be used to replace those elements lost from land by harvesting produce.

Concerns for the long-term effects of biosolids use in agriculture first arose due to the presence of non-essential elements (e.g. cadmium, mercury, etc.). Research on these issues commenced internationally in the 1970s, and since then our knowledge of the effects of contaminants in biosolids has improved dramatically. However, the relevance of this body of work to Australian soils and agricultural production systems was still not clear.

In the late 1980s and 1990s concern for soil and food quality in Australia grew due to local exceedances of food quality standards for cadmium for certain crops and the conflicting reports in the scientific literature of the level of protection offered by current biosolid guidelines. It was also recognised that data on risks due to metals in biosolids were restricted to a few sites in New South Wales, and Australia had little evidence to confirm that these relationships were being under- or over-protective across the diverse range of soils and cropping systems in Australian agriculture. It was under this climate that the National Biosolids Research Program (NBRP) was formed in 2002, to coordinate research relating to the benefits and risks of using biosolids in agriculture.

Background

The NBRP was a coalition of seven research agencies around Australia, with support from several metropolitan and regional water authorities, and from several state environmental and natural resource management agencies. Prior to establishing the NBRP a preliminary hazard assessment was conducted to determine the metals that would be the focus of the program.

The hazard posed by those metals that do not bioaccumulate (do not increase in concentration as food chains are ascended) was determined by calculating a hazard quotient: dividing the maximum or the mean concentration of the metals in a range of biosolids from each state participating in the NBRP by their corresponding soil limits (termed Ecological Investigation Levels – EILs) from the National Environment Protection (Assessment of Site Contamination) Measure (NEPC, 1999). The metals were then ranked from those posing the greatest hazard to the lowest hazard (Table 1). Copper and zinc were the two metals that posed the greatest hazard.

For cadmium and mercury, that bioaccumulate, the hazard is greatest to organisms high in food chains. Thus the hazard was assessed by comparing the dietary exposure of humans expressed as a percentage of the then current food safety limits set by Food Standards Australia New Zealand (FSANZ, 2002). The most recent Total Diet Survey results for metals (FSANZ, 2003) shows that cadmium is approximately twice as hazardous to human health (via food) as mercury.

Table 1. The maximum and mean concentrations (dry weight basis) of metals in biosolids that do not bioaccumulate, their soil limits (EILs) and the ranking of the hazard they pose. The element with a ranking of 1 poses the greatest hazard and the element with a ranking of 7 poses the lowest hazard.

Element	Maximum conc. in biosolids (mg/kg)	Mean conc. in biosolids (mg/kg)	EIL (mg/kg)	Ranking of hazard based on maximum conc.	Ranking of hazard based on mean conc.
arsenic	12	5	20	6	6
chromium	307	92	300	4	5
copper	1500	645	100	1	1
lead	190	60	600	7	7
manganese	370	180	500	5	4
nickel	80	32	60	3	3
zinc	2000	740	200	2	2

Therefore cadmium, copper and zinc were selected as the three metals to be the focus of the NBRP.

Cadmium contamination of agricultural soils in Australia has become increasingly important in recent years due to increased public awareness and concern for food and land quality. Cadmium residues in foods are regularly monitored by both national and international agriculture and health agencies. With Cadmium the principal concern is potential affects on human health.

Copper and zinc were also selected for study as these elements are at relatively high concentrations in biosolids and concern had been expressed internationally that these may affect soil microbial health. With copper and zinc the principal concern is potential affects on environmental health.

As well as potential risks, the benefits of nutrients and organic matter in biosolids on crop growth were also assessed, with various cropping systems around Australia evaluated. The NBRP has subsequently moved onto examining potential risks from pathogens, pharmaceuticals, endocrine disrupting compounds and personal care products.

General methods

A key feature of the NBRP was that laboratory and field experimentation had a common experimental design, and analyses were shared between the research partners, allowing integration of the data and extrapolation to a wide range of soil and crop environments in Australia.

Seventeen field sites were established (Figure 1), with production systems varying from sub-tropical sugar cane production in northern Australia to Mediterranean dryland cereal production in the south.

Plots were established which received increasing rates of both urban biosolids (conducted in triplicate) and soluble metal salts (replicated 2-4 times depending on the metal). Fifteen sites were amended with biosolids, twelve were amended with metal salts and biosolids and one site was amended only with metal salts. The sites spanned a diverse range of climates, from tropical (the Qld sites) to temperate (the NSW and Vic sites) and Mediterranean (the SA and WA sites), and with soils having a wide range of physico-chemical characteristics (Table 2). Because of these site differences, the range of metal concentrations used differed at each field site.

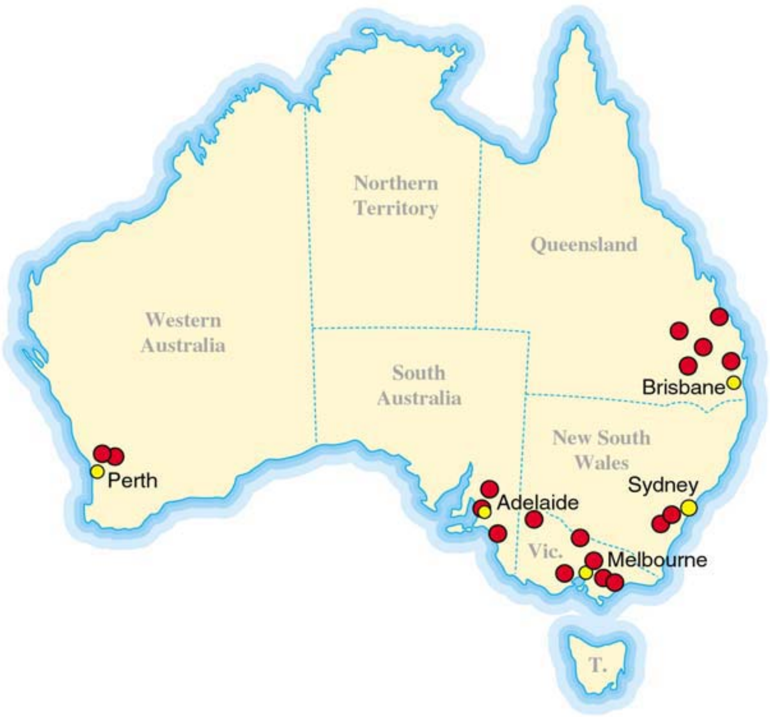

Figure 1. Locations of field sites in the National Biosolids Research Program

Table 2. Details of the field trials and selected soil properties (dry weight basis) for sites of the National Biosolids Research Program

Field site	Location[a]	pH (0.01 M $CaCl_2$)	Organic carbon (%)	Clay content (%)	CEC[b] ($cmol_c$/kg)
Avon	SA	7.6	1.2	12	10.0
Brennans	WA	5.4	0.9	4	3.2
Bundaberg	Qld	4.5	1.4	16	5.0
Cecil Plains	Qld	7.3	1.4	66	61.0
Dookie	Vic	4.9	2.0	23	13.0
Dutson Downs	Vic	4.0	5.7	5	11.6
Esk	Qld	5.0	na	25	1.0
Flat Paddock	NSW	4.4	1.2	17	7.8
Kingaroy	Qld	5.0	1.8	41	16.5
Lowood	Qld	6.2	5.5	58	54.7
Melton	Vic	4.7	2.6	31	14.1
Mildura	Vic	7.9	0.6	11	8.3
Night Paddock	NSW	5.1	3.4	24	17.4
Pakenham	Vic	4.9	5.7	26	16.6
Spalding	SA	6.3	1.9	27	17.7
Tintinara	SA	6.3	1.8	10	10.3
Wilsons	WA	4.8	2.6	6	5.0

[a] SA = South Australia, NSW = New South Wales, Qld = Queensland, Vic = Victoria, WA = Western Australia. [b] CEC = cation exchange capacity

Biosolids application rates were based on the Nitrogen Limited Biosolids Application Rate (NLBAR) which is the predicted amount of biosolids that can be added to a soil so there is no predicted net accumulation of mineral nitrogen after one year (i.e. the amount of mineralisable nitrogen added to the soil by the biosolid addition is equal to the amount taken up by the crop in one year).

Biosolids used in the trials were typical of those used in reuse programs around Australia, and included wet slurries, dry cakes and lime-stabilised products. Chemical composition and sources of the biosolids are shown in Table 3.

All biosolids field trials consisted of eight treatments – a control (un-amended soil), a fertiliser control (according to normal farmer practises in the region), 0.25 or 0.5, 1, 1.5, 3 and 4.5 NLBAR as a single application on commencement and a 1.5 NLBAR per year repeat application over 3 years.

Table 3: Sources and chemical properties of biosolids (dry weight basis) used in the National Biosolids Research Program.

Biosolids source	pH	Total C (%)	Total N (%)	Total P (%)	Total Cd (mg/kg)	Total Cu (mg/kg)	Total Zn (mg/kg)	Total Al (mg/kg)
SA Bolivar – air dried	7.4	6.3	0.8	0.8	1.8	315	435	-
SA Bolivar - lagoon	7.4	8.6	1.0	1.0	2.2	340	500	-
Vic Goulbourn Valley Water	7.1	6.5	0.8	0.3	1.4	65	180	40 000
Vic North East Water	5.0	11.6	2.0	2.5	0.9	100	300	31 000
Vic Central Gippsland Water	5.6	20.4	2.8	1.1	<0.5	70	150	18 000
Vic Central Highlands Water	4.9	19.0	2.3	2.0	1.1	800	2000	17 000
Vic East Gippsland Water	4.6	10.6	1.2	0.3	1.0	150	290	44 000
Vic Western Water	6.1	19.0	2.3	1.8	< 0.5	320	750	62 000
Vic South East Water	5.0	9.6	1.0	0.3	2.0	522	1070	-
Vic Yarra Valley Water	8.3	10.8	1.0	1.7	< 0.2	160	246	-
Vic Lower Murray Water	5.3	10.0	1.5	0.6	1.4	220	330	13 000
NSW Malabar	7.6	20.3	1.6	1.4	5.4	420	650	5 000
NSW Bondi	5.9	28.7	2.5	1.1	4.6	880	870	5 000
Qld Noosa	6.8	27.2	4.8	4.7	1.9	355	495	14 000
Qld Luggage Point	6.6	32.8	5.7	2.7	3.5	830	1705	11 700
WA Woodman Point	6.9	32.2	5.2	1.5	2.0	1500	900	3 750
WA Beenyup	6.8	34.7	5.5	2.0	1.4	1170	615	3 450

Cd = cadmium, Cu = copper, Zn = zinc.

Rates of cadmium salts added to soil were designed to produce a range of soil solution cadmium concentrations, determined by preliminary experiments. Note that these rates were well below those which could lead to toxicity to plants or soil organisms, and were designed to provide sufficient cadmium to lead to crop cadmium accumulation up to, and exceeding, current food limit values as set by Food Standards Australia New Zealand (FSANZ).

Copper and zinc salts were added at 11 rates in duplicate at each of 12 sites. The concentrations of copper and zinc added were based on the results of laboratory-based toxicity tests and selected so that the effects on plants would range from no effect through to 100% lethality.

Various crops were grown on the plots depending on local agronomic and climatic conditions – barley, canola, cotton, grapes, grasses, maize, millet, oats, pasture, peanuts, sorghum, sugar cane, triticale and wheat. Crops were grown using best agronomic practices, harvested, and then edible portions of crops separated, dried, and after acid digestion, metal concentrations in plant shoots and/or edible portions were determined. Critical soil concentrations of copper and zinc at which plant growth and crop yield were affected were determined for each site and toxicity was assessed in relation to soil properties. The food chain risk of biosolids cadmium was determined by developing critical soil concentrations at which crop cadmium concentrations were predicted to exceed the maximum level in Australia as prescribed by the Australian Food Standards Code (FSANZ, 2005).

Soil samples were taken from under the crop immediately after each harvest each year. All soil samples were analysed for total metals and a range of chemical and physical characteristics. Each year, soil pore waters were also extracted and pH, electrical conductivity (EC) and metal concentrations in solution determined.

The functioning of soil micro-organisms in relation to carbon and nitrogen cycling was also assessed using two microbial function assays – substrate induced respiration and substrate induced nitrification. These microbial functions are important in the nutrient deficient Australian soils. Critical soil concentrations of copper and zinc at which these microbial functions are affected were determined for each site and toxicity was assessed in relation to soil properties. At selected sites, mineralisation and movement of biosolids -nitrogen was assessed and mass balances of nitrogen and phosphorus were calculated.

A series of published scientific papers on outcomes from the NBRP have been produced (Appendix I), and from these, guidelines for the use of biosolids in agriculture have been developed. These relate to maximum permissible concentrations of metals in soils receiving biosolids, and to predictions of nutrient release from biosolids at selected sites.

Research is ongoing to determine whether refinements to biosolids guidelines are also appropriate for the management of pathogens and organic contaminants.

Recommended improvements in guidelines to minimise risks due to cadmium, copper and zinc in biosolids

As noted above, potential risks due to cadmium in biosolids are expressed first through the food chain. Risks from copper and zinc in biosolids are expressed first though direct toxicity to plants or soil organisms.

Cadmium

Current maximum permitted concentrations of cadmium in soils receiving biosolids and used for food crop production vary across state jurisdictions, from 0.7 mg/kg in Tasmania to 3 mg/kg in South Australia.

Maximum levels (MLs) for cadmium have been set for several crops in Australia by FSANZ (Table 4).

Table 4. The Australian cadmium food standards (FSANZ, 2005).

Food	Maximum levels (mg/kg fresh weight)
Chocolate	0.50
Kidney	2.50
Liver	1.25
Meat	0.05
Leafy vegetables, peanuts, rice, root and other tuber vegetables, and wheat	0.10

Use of biosolids on crops prone to accumulate high concentrations of cadmium is not recommended i.e. leafy vegetables, root crops (onions, carrots, etc.), tuber crops (potato) and certain broad-acre crops such as peanuts.

The main broad-acre crops in Australia which have food cadmium standards are wheat and rice. Experimentation in the NBRP focussed on wheat as areas growing rice rarely receive biosolids due to lack of proximity to urban centres.

Uptake of biosolids cadmium was found to be dependent on soil physical and chemical properties, principally soil pH and soil clay content. Soils with low pH and low clay contents allowed greater transfer of biosolid cadmium to grain.

In saline soils (which none of the NBRP soils are) increased salinity increases the bioavailability of cadmium to plants. Elevated soil salinity can arise due to human activities such as irrigating with saline water or due to rises in saline groundwaters causing dryland salinity. Repeated use of biosolids is not recommended in these saline areas. Best management plans (BMPs) for minimising the uptake of cadmium by agricultural products are available on the website of the Australian National Cadmium Minimisation Strategy (http://www.cadmium-management.org.au/publications.html).

A graded series of maximum total cadmium concentrations in soil were developed to protect grain from exceeding the FSANZ MLs (Table 5). The soil pH and clay content values used in Table 5 to determine the recommended maximum permitted total soil cadmium concentration are the values of the site where biosolids are being considered for application before application occurs.

Table 5. Recommended maximum permitted total cadmium (Cd) concentrations in soils receiving biosolids to ensure wheat grain does not exceed the Australian cadmium food standards (FSANZ, 2005).

	Recommended maximum permitted total cadmium in soils receiving biosolids (mg Cd/kg soil)		
pH	Clay content (%)		
	5	25	50
4.5	0.50	1.1	1.9
5.5	0.6	1.3	2.0
6.5	0.80	1.4	2.2
7.5	0.9	1.5	2.3
8.5	1.1	1.7	2.5

Copper

Current maximum permitted concentrations of copper in soils receiving biosolids and used for food crop production vary across state jurisdictions, from 100 to 300 mg/kg. There are no Australian maximum levels (MLs) for copper in food (FSANZ, 2005).

The main concern with copper is environmental impacts. Therefore, in the NBRP we focussed on the impacts of copper on crop growth, crop yield and microbial function (i.e. microbial nitrification and microbial respiration).

Toxicity of copper to wheat was found to be dependent on soil physical and chemical properties, principally soil pH and soil organic carbon content. Plants showed reduced grain yield and growth at lower concentrations of copper in soils with low pH and low organic carbon contents than in soils with high pH and high organic carbon content.

The toxicity of copper to microbial respiration was not affected by soil properties whereas microbial nitrification was affected by soil pH and cation exchange capacity. Microbial nitrification was inhibited at lower concentrations in soils with low pH and low cation exchange capacity than in soils with high pH and high cation exchange capacity. Microbial respiration was more sensitive to copper than microbial nitrification.

A graded series of suggested maximum added copper concentrations in soil to which biosolids have been added were developed (Table 6). The suggested values are a combination of values derived from protecting plants and protecting microbial function. The organic carbon content of soils amended with biosolids will decrease over time back to the content before the biosolids were added. Thus the soil pH and organic carbon content values used in Table 6 to determine the recommended maximum permitted added copper concentrations in soils are the values of the site where biosolids are being considered for application before application occurs.

Table 6. Recommended maximum permitted added copper (Cu) concentrations in soils receiving biosolids to prevent toxic effects to plants and micro-organisms. The suggested total permitted copper concentration is obtained by adding the ambient background concentration to the values presented.

	Recommended maximum permitted added copper concentration in soils receiving biosolids (mg added Cu /kg soil)		
pH	Organic carbon content (%)		
	1	2	5
5.0	25	50	135
5.5	40	75	175
6.5	90	185	200
7.5	205	230	230
8.0	245	245	245

Zinc

Current maximum permitted concentrations of zinc in soils receiving biosolids and used for food crop production vary across state jurisdictions, from 200 to 250 mg/kg. There are no Australian maximum levels (MLs) for zinc in food (FSANZ, 2005).

The main concern with zinc is environmental impacts. Therefore, the NBRP focussed on the impacts of zinc on crop growth, crop yield and microbial function (i.e. microbial substrate induced nitrification and substrate induced respiration).

The toxicity of zinc to wheat was found to depend on soil physical and chemical properties, principally soil pH and cation exchange capacity. Plant show reduced grain yield and growth at lower concentrations of zinc in soils with low pH and low cation exchange capacities than in soils with high pH and high cation exchange capacities.

The toxicity of zinc to microbial respiration was not affected by soil properties whereas microbial nitrification was affected by soil pH. A decrease in microbial nitrification rates occurred at lower concentrations of zinc in soils with low pH than in soils with high pH. As with copper, microbial respiration was more sensitive to zinc than microbial nitrification.

A graded series of suggested maximum added zinc concentrations in soil which biosolids have been added were developed (Table 7). The suggested values are a combination of values derived from protecting plants and protecting microbial function. The soil pH and cation exchange capacity values used in Table 7 to determine the recommended maximum permitted added zinc concentrations in soils are the values of the site where biosolids are being considered for application before application occurs.

Table 7. Recommended maximum permitted added zinc (Zn) concentrations in soils receiving biosolids to prevent toxic effects to plants and micro-organisms. The suggested total permitted zinc concentration is obtained by adding the ambient background concentration to the values presented.

	Recommended maximum permitted added zinc concentration in soils receiving biosolids (mg added Zn /kg soil)			
pH	Cation exchange capacity ($cmol_c$/kg)			
	3	10	20	60
4.5	20	45	75	165
5.5	38	90	145	300
6.5	70	165	265	300
7.5	130	300	300	300
8.0	180	300	300	300

Recommendations regarding nutrients

The importance of determining nutrient availability in biosolids cannot be overstated since it is almost always the limiting factor in determining annual biosolids application rates. While there are undoubted benefits to cropping systems from the nutrients (nitrogen and phosphorus in particular) contained in biosolids (Table 3), it is difficult to predict their plant availability and thus develop appropriate management guidelines - especially when trying to ensure off-site impacts are minimised. This is primarily because the availability of nutrients in biosolids is a function of: soil properties; prevailing climatic conditions (moisture, temperature); the biosolids treatment process; and the demand for the nutrients by crops. Nutrients were not the principal focus of the NBRP however, work done primarily in Queensland demonstrates some of the limitations in the current biosolids guidelines in Australia and highlights the need for further work to refine guidelines for biosolids nutrient management.

Nitrogen

Currently, nitrogen and the corresponding NLBAR is one factor that limits the annual application rate of biosolids. The method generally used to calculate the NLBAR in Australia, assumes either 15% (anaerobically digested biosolids) or 25% (aerobically digested biosolids) of the organic nitrogen (N) in biosolids will be converted to mineralised N (i.e. plant available ammonium and nitrate) in one crop season after biosolids application. Field studies conducted during spring/summer growing seasons in southern Queensland showed that mineralisation rates could be up to 3 times those suggested in the current guidelines. Subsequent laboratory studies confirmed the field results.

The rapid mineralisation of N from biosolids under subtropical conditions causes mineral N to accumulate in the soil at far greater rates than is required to meet plant demands. The mineral N is thus vulnerable to offsite migration, either by leaching (especially in sandy soils typical of those supporting sugarcane crops) or to the atmosphere as nitrogen gas or nitrous oxide gas as a result of denitrification (conversion of NO_3-N back to nitrogen gases, N_2 or N_2O) and/or volatilisation of ammonia. Significant leaching losses of N could lead to soil acidification.

Laboratory studies in which biosolids were incorporated into soil showed that denitrification losses were much greater than losses from volatilisation and represented as much as 30% of the biosolids N in a 3 month period. Losses were greater when soils were wet, and were exacerbated by the presence of polymers used in the biosolids dewatering process.

These gaseous N losses are not only losses of a valuable nutrient, but could have other impacts if significant production of nitrous oxide (N_2O) occurs, as this is a potent greenhouse gas. Attention needs to be paid to either regulating the rate of organic N mineralisation in biosolids once incorporated into soil, or better defining the rate of N mineralisation that will occur from biosolids under different soil and climatic conditions. This work would need to adopt a national approach like the current NBRP, in order to cover the range of temperature and soil moisture conditions encountered in Australian field conditions, as well as the variation in biosolids properties resulting from various treatment processes.

Phosphorus

While the absolute amount of nutrients in biosolids is an important consideration in assessing the benefits of biosolids application to land, the relative amounts and bioavailability of those nutrients compared to crop requirements are also significant issues. The large amounts of phosphorus (P) contained in biosolids (Table 3) are a valuable nutrient input to support crop production, but when biosolids are applied at rates to satisfy N demand by a crop (NLBAR), the resulting rate of P application can be excessive. This is illustrated by the rates of N and P removal in harvested produce, with 5-7 times as much N removed as P in the NBRP studies. The resulting accumulation of P in the soil profile at sites where biosolids are applied is exacerbated by re-application of biosolids to maintain soil N fertility.

In soils in which the capacity to store P is limited (e.g. lighter textured, sandy soils), the excess P accumulating from biosolids application programs based solely on N availability would result in a significant risk of offsite movement (in runoff and/or leachate) that could contribute to eutrophication of water bodies. There is therefore a strong case to develop guidelines based on a P limiting biosolids application rate (PLBAR) that could be invoked under specific soil conditions. The primary role of soil properties in determining P retention characteristics, combined with the fact that the majority of P in biosolids is in inorganic forms, suggests that a national approach to development of a PLBAR calculation is essential.

Implications of Accepting the Recommended Limits to the Biosolids Industry

The suggested limits for cadmium, copper and zinc reflect the effect that soil properties have on toxicity and uptake of metals. Therefore, soils with a combination of low pH, low organic carbon content, low clay content and low cation exchange capacity are considered to be at high risk from the application of biosolids. Such soils, depending on their exact soil properties, should receive very limited additions. While soils with high soil pH, high organic carbon content, high clay content and high cation exchange capacity can receive considerable additions of biosolids and are considered to be at low risk from biosolids application.

Examples of how much biosolids can be added to soil were calculated for four sites from the NBRP which represent high risk, high to moderate, moderate and low risk soils (Table 8). Copper and in one case zinc were the metals that limited the application of biosolids. High risk soils can receive very limited amounts of biosolids before exceeding the metal soil limits. Whereas moderate to low risk soils can have many repeat applications of biosolids over a prolonged period.

Table 8. Sample calculations of the maximum biosolids mass that can be applied to representative low to high risk soils of the National Biosolids Research Program, based on the total soil limits for each metal. The soil properties for each site (from Table 2) were used to determine the total soil limits for cadmium from Table 5, for copper from Table 6 and for zinc from Table 7. An additional step for copper and zinc was to add the ambient background concentration to the limits obtained from Tables 6 & 7 respectively. The metal that restricts the amount of biosolids that can be applied is indicated in parentheses in the eighth column (Cd = cadmium, Cu = copper and Zn = zinc). All values reported have been rounded off.

Risk	Representative site	Metal	Total soil limits (mg/kg)	Concentration of metals in biosolids applied at each site (mg/kg)	Mass of biosolids (T) that can be applied per ha
Low	Cecil Plains	Cd	2.3	1.9 - 3.5	
		Cu	258	355 - 830	280 – 970 (Zn)
		Zn	370	495 - 1700	
Moderate	Spalding	Cd	1.4	1.8 - 2.2	
		Cu	176	315 - 340	675 – 730 (Cu)
		Zn	290	435 - 500	
High	Flat Paddock	Cd	0.9	4.6 - 5.4	
		Cu	30	420 - 880	40 – 90 (Cu)
		Zn	71	650 - 870	

Summary

Critical soil concentrations for cadmium, copper and zinc at which adverse effects on plant quality, crop production and microbial processes commenced were determined in soils from seventeen field-sites located in the major agricultural regions of Australia. These critical concentrations for each metal were affected by soil properties such as soil pH, organic carbon content, clay content and cation exchange capacity. A series of recommended soil specific limits for cadmium, copper and zinc in soils that receive biosolids were derived using data from all the field-sites. These limits identified that acidic soils with low organic carbon, low clay content or low cation exchange capacity have low critical soil metal concentrations. The critical soil concentrations increased as the pH, organic carbon content, clay content or cation exchange capacity of soils increased. Depending on the soil properties at a site the recommended limits for cadmium, copper and zinc can be considerably smaller or larger than the current limits used in the various Australian jurisdictions. The amount of biosolids that can be added to soils varies with the concentrations of metals in the biosolids and the properties of the soil. Example cumulative amounts of biosolids that could be added to high risk soils are 20 – 50 t/ha which increase to 230 – 790 t/ha for low risk sites. The findings show that the land application of biosolids can continue to be conducted sustainably provided care is taken in the selection of sites to receive biosolids.

The nutrients in biosolids undoubtedly have beneficial effects on plant growth yet potential deleterious effects need to be carefully managed. In warm, subtropical regions the rapid mineralisation of organic N can lead to concentrations of mineral N in soil that exceed plant requirements. Phosphorus concentrations in soil usually increase when biosolids application rates are determined on the basis of N supply. Thus in sandy, highly permeable soils there is considerable potential for off-site migration of N and P. It is recommended that a national approach, such as the NBRP, is required to address these aspects of nutrient management in biosolids applied to land.

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Acknowledgements

The authors wish to acknowledge Prof. Nick Basta (Ohio University Prof. Murray McBride (Cornell University, USA), Dr Graham Merrington (Watts and Crane Associates, United Kingdom), Dr Hamish Reid (South East Water Limited, Victoria), Prof. Erik Smolders (Katholieke Universiteit, Leuven, Belgium) for reviewing the Position Paper and associated technical documents. We also wish to acknowledge the following organisations for their support of the Australian National Biosolids Research Program.

Appendix

The appendix contains published and unpublished technical documents that provide detail of the methods used, the rationale, the results of the analyses undertaken, and conclusions of the NBRP. It also contains copies of the final reports of the various state components of the NBRP and other papers which provide additional supportive information. It is recommended that the articles arising from the NBRP are read in the order presented in the Appendix.

Articles rising from NBRP

Heemsbergen DA, Warne MStJ, McLaughlin MJ, Whatmuff M, Barry G, Bell M, Nash D, Pritchard D, Penney N. *In prep a*. A new framework for deriving guidelines for soil and soil amendments: Application to Cu and Zn phytotoxicity data for Australian soils and biosolids.

Heemsbergen DA, McLaughlin MJ, Warne MStJ, Whatmuff M, Barry G, Bell M, Nash D, Pritchard D and Penney N. *In prep b*. Bioavailability of zinc and copper in biosolids compared to their soluble salts.

McLaughlin, M.J., Whatmuff, M., Warne, M.St.J., Heemsbergen, D., Barry, G., Bell, M., Nash, D., Pritchard, D., 2006. A field investigation of solubility and food chain accumulation of biosolid-cadmium across diverse soil types. *Environmental Chemistry* 3: 428-432.

Heemsbergen DA, Warne MStJ, McLaughlin MJ, Broos K. *in prep c*. Technical Note: The effect of time since metal salts addition on the toxicity of Cu and Zn to wheat and microbial function.

Whatmuff M, McLaughlin M, Heemsbergen DA, Warne M. *In prep.* Chemical ageing of applied metal salts: Cd, Cu and Zn. *In prep.*

Broos K, Warne MStJ, Heemsbergen DA, Stevens D, Barnes MB, Correll RL, McLaughlin MJ, 2007. Soil factors controlling the toxicity of Cu and Zn to microbial processes in Australian soils. *Environmental Toxicology and Chemistry* 26: 583-590.

Warne MStJ, Heemsbergen D, Stevens D, McLaughlin M, Cozens G, Whatmuff M, Broos K, Barry G, Bell M, Nash D, Pritchard D, Penney N. *In press.* Modelling the toxicity of Cu and Zn salts to wheat in fourteen soils. *Environmental Toxicology and Chemistry. In press.*

Warne MStJ, Heemsbergen D, McLaughlin MJ, Bell M, Broos K, Whatmuff M, Barry G, Nash D, Pritchard D and Penney N. *Submitted.* Models for the field-based toxicity of Cu and Zn salts to wheat in eleven Australian soils and comparison to laboratory-based models. *Submitted* to *Environmental Pollution.*

Warne MStJ, Broos K, Heemsbergen DA and McLaughlin MJ. *In prep a.* Technical Note: Rationale and methods for deriving the microbial toxicity based soil and biosolids quality guidelines. *In prep.*

Guixin Pu, Mike Bell, Glenn Barry and Peter Want. *In prep a.* Fate of applied biosolids nitrogen in a cut and remove forage system on an alluvial clay loam soil. *In prep.*

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NBRP State Component Reports

Barry M and Bell M. 2006. Sustainable biosolids recycling in South East Queensland. Final project report to Brisbane Water and SEQROC Biosolids Management Project Group. 112p.

Butler C, Nash D, Hannah M, Cody J, Warne MStJ and McLaughlin MJ. 2007. The National Biosolids Research Program – Victoria. Final Report - June 2007. 93p.

Heemsbergen D, Broos K, Whatmuff M, Warne MStJ, McLaughlin MJ, Stevens D, Smart M, Fiebiger C, Baldock C, Cozens G, Tomczak B, Daly A. 2007. Final report for the South Australian Component of the National Biosolids Research Project. Client report to South Australian Water and to United Water. 127p.

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