

**The National Biosolids Research Program:
Research Studies on the Impact of Heavy Metals on
Sustainable Fertilisation and Intensive Agricultural
Applications of Biosolids**



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Executive Summary

This is the final report of the Western Australian component of the National Biosolids Research Program (NBRP) covering three consecutive years of field experimentation (2003-2005). The experiment investigated metal uptake of cadmium, copper and zinc and nutrients in wheat and canola crops following the application of biosolids produced in Western Australia to assess their suitability for long term agricultural land application. Large quantities of biosolids are used in agriculture in Western Australia annually, with 73% of the total 20,313 dry tonnes (t) in the 2005/06 year. This comprised of Beenyup WWTP 5,028 dry t; Woodman Point WWTP 6,628 dry t; and Subiaco WWTP 8,657 dry t. Biosolids from the Woodman Point and Beenyup Wastewater Treatment Plants (WWTPs) in Western Australia were used in the major investigation, although a pilot study commenced in 2005 examined biosolids from Subiaco WWTP. This final report supersedes preliminary progress reports submitted to the Water Corporation in July 2005 and February 2006.

All research data collected during this study for the Western Australian component is stored directly onto a national database managed by CSIRO Land and Water in South Australia

<http://www.awa.asn.au/Content/NavigationMenu2/ResourceCenter/BiosolidsManagement/NationalBiosolidsResearchProgram/default.html>. The Western Australian investigation forms part of a larger project consisting of several sites around Australia under the leadership of CSIRO Land and Water, South Australia. The project has been funded by the Water Corporation and is being carried out by Curtin University of Technology, Muresk Institute in accordance with the NBRP methods document (Smart et al. 2002).

The research consisted of a metal-salt component and a biosolids component. The quantity of metals applied to the metal-salt trials was much higher compared with those applied to the biosolids treatments. The metal-salt trials were designed to provide either a plant phytotoxicity response (copper or zinc), or to produce crops with edible tissue concentrations (cadmium) above maximum permitted levels in food. Metal-salts were selected as they are expected to be more bio-available than those applied with organic waste materials and thus provide for a 'worst case' scenario. The biosolids trials were designed to provide information on the yield benefits from the addition of biosolids nutrients, while at the same time comparing the metal uptake responses with those of the pure metal-salts (Whatmuff et al. 2004).

The experiment was conducted on two sites on the property of O, P & J Cocking at Gillingarra (approximately 20 km south of Moora). Overall there were little differences between Woodman Point or Beenyup biosolids applied at multiples of the Nitrogen Limited Biosolids Application Rate (NLBAR). At some application rates of Beenyup biosolids, there were minor increases in crop yields compared with Woodman Point biosolids, more noticeably in the final year.

Generally there were no significant differences in wheat yield between the 1xNLBAR that had been applied in year one and the inorganic fertiliser treatment (100 kg/ha DAP + 100 kg/ha urea) that had been applied annually every year over the three year investigation. The only exceptions were that canola grown in 1xNLBAR in year one yielded higher than the fertiliser treatment and that canola grown in 1xNLBAR in year

two yielded less than the fertiliser treatment. The results would indicate therefore that over a three year period biosolids continued to release plant nutrients (i.e. nitrogen and phosphorus) at a rate equivalent to an annual application of standard inorganic fertiliser for wheat, but the residual value for canola was inadequate. At biosolids application rates of higher than 1xNLBAR however, crop yields were mostly improved. The NLBAR translated to 7 dry t/ha of Beenyup biosolids and 6.5 dry t/ha of Woodman Point biosolids to provide approximately 70 kg/ha of plant available N. By the third season, crop yields were higher where biosolids were applied annually (i.e. 1.5xNLBAR repeat) compared with an equivalent initial amount of biosolids (i.e. 4.5x NLBAR). Further work needs to be conducted to validate nitrogen mineralisation rates.

Preliminary results show that at high rates of biosolids, up to 4.5xNLBAR, the maximum allowable soil contaminant concentration (MACC) for Cd, Cu and Zn for biosolids amended soils used for food production was not exceeded. The metal concentrations measured in soil samples from biosolids amended soils were below the LC50 toxicity threshold values determined from the metal-salt trial.

A sub-project to investigate the liming effect and nutritional value of lime-amended biosolids (LAB) produced from Subiaco WWTP was commenced in 2005. A total of nine LAB and agricultural lime treatments were established on an acidic red loam at Wongamine (20 km north-east of Northam) to provide preliminary data as to the effect of LAB on the growth and yield of wheat and to assess the neutralising value of the lime on soil pH. The results of this work will be reported fully in the subsequent research program.



A summary of the major milestones as set out in the scope of the project is given in Table 1. All milestones were achieved, with three years of crop and soil data collected and reported.

Table 1. Milestones for project summarised for the 2003 to 2007 period.

	Feb-03	May-03	Jun-03	Sep-03	Dec-03	Mar-04	Jun-04	Sep-04	Dec-04	Mar-05	Jun-05	Sep-05	Dec-05	Mar-06	Jun-06	Sep-06	Dec-06	May-07	
State coordination meetings and progress reports	█																		
National Coordination meetings. Communication of outcomes to Environmental and Health Depts.			█	█	█		█		█				█					█	█
Baseline data detailing threshold concentrations of Cd, Cu, Zn and Al added to agricultural soils (Laboratory based).			█	█	█		█												█
Establish field trials and taking of initial soil samples.		█	█	█															
Plant crops			█	█			█				█								
Monitor crops growth and Harvest crops				█	█		█	█	█			█	█	█					
Take appropriate soil samples, prepare and analyse samples as required						█	█	█	█	█	█			█	█	█			
Data analysis and interpretation.			█	█	█		█	█	█	█	█	█	█	█	█	█			
Publication of data interpretation and communication of results.			█	█	█		█	█	█	█	█	█	█	█	█	█			
Baseline data detailing threshold concentrations of Cd, Cu, Zn and Al added to agricultural soils (Field based).																			█
Integrate data and develop code of practice for safe and sustainable use of biosolids																			█
Long-term consequences of application of biosolids to agricultural soils assessed																			█
Recommendation for alternative land uses, if required.																			█
Assessment of risks of other metals in biosolids																			█
Final report																			█

Reports and conference papers

- A two-day workshop for collaborators in the National Biosolids Research Program and interested regulatory authorities and industry bodies was held in Brisbane, August 2003. Presentations were made by each of the state collaborators, including the authors of this report.

- The National Biosolids Research Program of which the Water Corporation funded research is part of delivered 11 oral presentations at the Australian Water Association (AWA) Biosolids Specialty Conference – II in Sydney in June 2004. Copies of the abstracts are attached in Appendix 1.
- One presentation was made from work arising from the National Biosolids Research Program – pathogen studies at the Australian Water Association (AWA) Contaminants of Concern in Water Conference at Canberra in June 2005. The abstract is attached in Appendix 2.
- Karen Crute published her honours thesis in 2004 through Curtin University of Technology titled, “Are pathogens present in wheat grain at harvest following the land application of biosolids?”
- Information regarding the NBRP project was presented at the recently formed Agricultural Research Western Australian (ARWA), Plant Nutrition Seminar at The University of Western Australia, August 2005, as attached in July 2005 Progress Report, Appendix 3.
- Team members belonging to the NBRP, including Western Australia contributed regularly to the National Biosolids Newsletter. The brochure promoting the National Biosolids Research Program is distributed at conferences and workshops throughout Australia and has been added to the AWA website - <http://www.awa.asn.au/NSIG/bio/biosolids.pdf>
- A two-day workshop for collaborators in the National Biosolids Research Program was held in Perth, Aug/September 2005, which was followed by a biosolids workshop aimed at interested regulatory authorities and industry bodies. Presentations were made by each of the state collaborators, including the authors of this report. The program also included a site tour to the NBRP Gilingarra sites and a forestry tour to Myalup (Appendix 1).
- A paper titled, ‘Biosolids: Black Gold in Western Australia’ by D. Pritchard, N. Penney and I. Dumbrell was presented at the New Zealand Land Collective Treatment Conference, March 2006. The paper outlines the research programs in WA and will be presented by D. Pritchard. The trip was funded by Curtin University (Appendix 2).
- A seminar was presented to the Northam Water Corporation by D. Pritchard on 21 December 2005.
- A paper summarising the LAB trial was presented at the Australian Water Association, Biosolids Specialty Conference III, Melbourne June 2006.

Budget

A summary of the budget is provided in Table 2.

Table 2. Summary of the annual budget for the 02/03, 03/04 and 04/05 financial year periods as of 20 August 2005.

	Year 1 (7/02 - 6/03)			Year 2 (7/03 - 6/04)				Year 3 (7/04 - 06/05)			
	Budget	Actual	Diff	Budget	B/Fwd	Actual	Diff	Budget	B/Fwd	Actual	Diff
Income - Water Corp	\$45,745.92	\$45,745.92	\$0.00	\$52,314.21	\$52,314.21	\$54,378.16	-\$2,063.95	\$53,311.78	\$51,247.83	\$51,247.83	\$0.00
Income - Pelletised Bios						\$10,000.00					
Income - Pathogen Res						\$ 9,066.00					
1.1 R&D Cost Recovery	\$5,512.72	\$5,614.17	-\$101.45	\$5,512.72	\$5,411.27		\$5,411.27	\$5,512.72	\$10,923.99	\$ 4,134.54	\$6,789.45
1.0 (a) Deborah Pritchard	\$7,187.19	\$4,091.55	\$3,095.64	\$6,708.02	\$9,803.66	\$5,565.43	\$4,238.23	\$6,976.30	\$11,214.53	\$ 2,755.09	\$8,459.44
(b) David Collins	\$17,170.73	\$7,547.33	\$9,623.40	\$18,232.19	\$27,855.59	\$29,691.06	-\$1,835.47	\$18,961.48	\$17,126.01	\$29,103.75	-\$11,977.74
2.1 (a) ICP Harvest	\$0.00		\$0.00	\$1,716.00	\$1,716.00		\$1,716.00	\$1,716.00	\$3,432.00		\$3,432.00
(b) ICP Grain	\$0.00		\$0.00	\$1,716.00	\$1,716.00		\$1,716.00	\$1,716.00	\$3,432.00		\$3,432.00
2.2 (a) Pathogen Transfer	\$8,000.00		\$8,000.00		\$8,000.00	\$5,250.00	\$2,750.00		\$2,750.00	\$ 2,750.00	\$0.00
(b) Total C	\$1,920.00	\$1,380.00	\$540.00	\$1,920.00	\$2,460.00	\$ 1,219.00	\$1,241.00	\$1,920.00	\$3,161.00		\$3,161.00
(c) Total N	\$1,344.00		\$1,344.00	\$1,344.00	\$2,688.00	\$ 1,219.00	\$1,469.00	\$1,344.00	\$2,813.00		\$2,813.00
(d) Bicarb P	\$960.00		\$960.00	\$960.00	\$1,920.00	\$ 1,219.00	\$701.00	\$960.00	\$1,661.00		\$1,661.00
(e) Mid Tilling ICP (+N)	\$0.00		\$0.00	\$2,112.00	\$2,112.00	\$ 3,648.00	-\$1,536.00	\$2,112.00	\$576.00	\$ 2,112.00	-\$1,536.00
(f) ICP Grain (+N)	\$0.00		\$0.00	\$2,112.00	\$2,112.00	\$ 346.00	\$1,766.00	\$2,112.00	\$3,878.00	\$ 5,972.00	-\$2,094.00
(g) ICP Harvest DM (+N)	\$0.00		\$0.00	\$2,112.00	\$2,112.00	\$ 156.00	\$1,956.00	\$2,112.00	\$4,068.00	\$ 4,162.00	-\$94.00
3.0 (a) Lab & Consumables	\$1,000.00	\$4,881.44	-\$3,881.44	\$3,000.00	-\$881.44	\$7,645.18	-\$8,526.62	\$3,000.00	-\$5,526.62	\$ 4,082.75	-\$9,609.37
(b) Seeding & Harvest	\$1,500.00	\$518.75	\$981.25	\$3,000.00	\$3,981.25	\$3,499.55	\$481.70	\$3,000.00	\$3,481.70	\$ 3,075.00	\$406.70
(c) Travel to/from site	\$4,664.00	\$4,437.85	\$226.15	\$5,382.00	\$5,608.15	\$5,863.70	-\$255.55	\$5,382.00	\$5,126.45	\$6,435.78	-\$1,309.33
(d) Meetings	\$2,000.00	\$526.36	\$1,473.64	\$2,000.00	\$3,473.64	\$ 6,262.42	-\$2,788.78	\$2,000.00	-\$788.78	\$ 2,875.41	-\$3,664.19
4.0 Pelletised Biosolids						\$ 4,259.18	-\$4,259.18	\$10,000.00	\$5,740.82	\$ 5,041.60	\$699.22
5.0 Pathogen Research							\$0.00	\$9,066.00	\$9,066.00	\$ 1,905.16	\$7,160.84

Field sites and methodology

Trial design

The field experiment was located north-east of Perth on 'Annadale', the property of O, P & J Cocking at Gillingarra. The design consisted of both a metal-salts and a biosolids component with full methodology reported in the methods document for the National Biosolids Research Program (Smart et al. 2002). The experiments were established on two paddock sites, known as Brennan's and Wilson's with GPS site locations as follows: Brennan's paddock (S 30° 52.758', E 116° 08.117') and Wilson's paddock (S 30° 51.856', E 116° 08.139'). Site selection was determined following intensive grid sampling and analysis as per Appendix 4, July 2005 progress report.

A description of the major physiochemical properties of the two soils is summarised in Table 3. The Brennan's site comprised on average 4% ironstone gravel stones (>2mm) in the 0-10 cm, whereas the Wilson's soil contained 48% ironstone gravel stones (>2mm) in the 0-10 cm depth. A full soil analysis for both sites is also available on the NBRP archive including electrical conductivity (EC), pH (0.01 M CaCl₂), total carbon (C) (Leco%), organic C (%), total N (%), exchangeable cations (cmol (+)/kg): calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K), and the proportion of clay (%), silt (%) and sand (%).

Table 3. Description of soil physiochemical properties of the <2 mm fraction of the top 10 cm of the Brennan's and Wilson's soils.

Parameter	Brennan's	Wilson's
EC (1:5) mS/m	2	5
pH (H ₂ O)	5.1 (prior to liming)	5.4
pH (CaCl ₂)	4.1 (prior to liming)	4.6
Sand %	94	91.5
Silt %	1.5	4
Clay %	4.5	4.5
OrgC (W/B) %	0.8	1.83
N total %	0.058	0.125
NH ₄ (mg/kg)	2	11
NO ₃ (mg/kg)	3	16
P total %	110	230
P (HCO ₃) mg/kg	27	34
PRI (mL/g)	4	13
Fe (AmOx) mg/kg	200	280
Al (AmOx) mg/kg	240	940
Ca (ex) cmol(+)/kg	0.72b	1.71b
Mg (ex) cmol(+)/kg	0.13b	0.22b
Na (ex) cmol(+)/kg	0.02b	0.06b
K (ex) cmol(+)/kg	0.12b	0.11b
Al (ex) cmol(+)/kg	0.46b	0.56b
Mn (ex) cmol(+)/kg	<0.02	0.02b

(CCWA 2002) Report 02A154/1-9

pH (CaCl₂) by 0.01 M CaCl₂ (Rayment & Higginson 1992i), EC (1:5) at 25°C (Rayment & Higginson 1992b); sand (2mm-0.02mm), silt (0.02mm-0.002mm), clay (<0.002mm) by plummet method in a suspension of soil in water with sodium hexametaphosphate/sodium hydroxide (McDonald et al. 1990), organic carbon (W/B) (%) by Walkley and Black (1934) (Rayment & Higginson 1992g), GSWC = Gravimetric soil water capacity, Total N (Blakemore, Searle & Daly 1987; Rayment & Higginson 1992f; Searle 1984), nitrate-N and ammonium-N extracted in 1M KCl (Rayment & Higginson 1992f), total P (Allen & Jeffery 1990; Murphy & Riley 1962), bicarbonate extractable P extracted by 0.5 M NaHCO₃ (1:100) (Colwell 1963; Rayment & Higginson 1992h), PRI (Allen & Jeffery 1990), PRI* = (P sorbed + Colwell P)/P solution (Allen, Barrow & Bolland 2001). Fe and Al extracted by 0.2 M ammonium oxalate pH 3.25 (Rayment & Higginson 1992c); calcium (Ca exchangeable), magnesium (Mg exchangeable), sodium (Na exchangeable), potassium (K exchangeable), aluminium (Al exchangeable), manganese (Mn exchangeable) extracted by 0.1M BaCl by method S21 (CCWA 2000).

mg/kg = milligrams per kilogram, mL/g = millilitres per gram, cmol (+)/kg =cmol (+) per kilogram, (mS/m = milliSiemens per metre).

Metal-salt trial

There were two replicates for each of the 12 Cu and Zn treatments and three replicates for each of the 5 Cd treatments, thus giving a total of 63 metal-salt plots per site (Figure 1) as described fully in the methods manual (Smart et al. 2002).

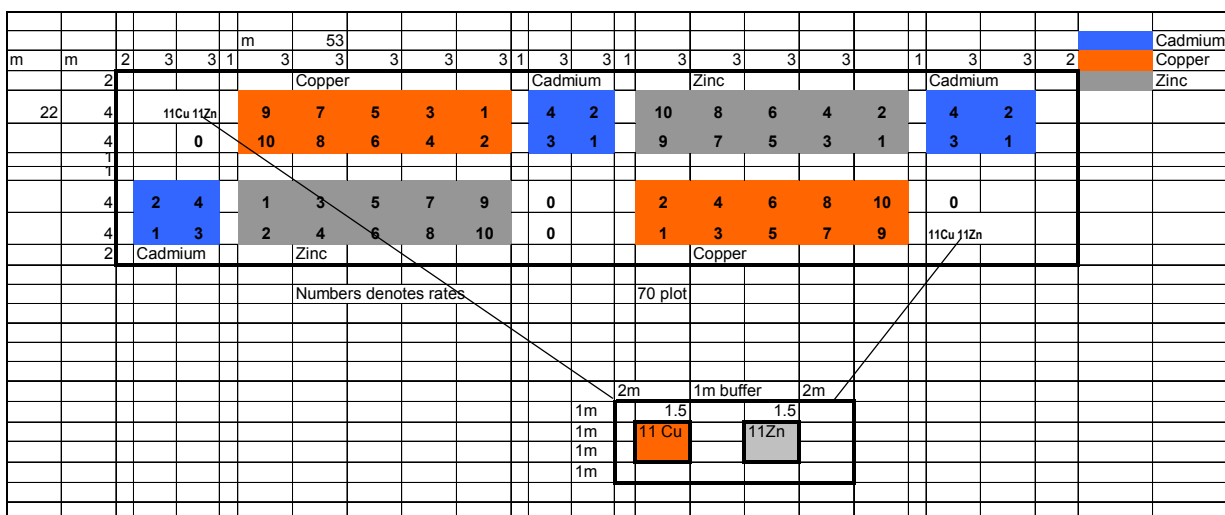


Figure 1. Detailed layout of Metal salt field experiment. Rates applied are calculated using the attached CD in the ACIAR Methods.xls spreadsheet (Metal rates tab). From Smart et al (2002)

The metal-salt trials used pure metal-salts to provide a series of soil metal concentrations (non-toxic to toxic) to establish a concentration-response relationship for copper (Cu) and zinc (Zn) in terms of plant phytotoxicity (Plate 1). The concentration ranges for cadmium (Cd) aimed to produce crops with edible tissues ranging in Cd concentration from below to above maximum permitted levels. By applying metals to soils in the form of pure metal-salts, the worst-case scenario for each metal was represented and it is assumed that the response to metals in all other waste materials will be a function of the metal-salt response (Whatmuff et al. 2004). Kris Broos (CSIRO Land and Water, Adelaide) previously determined toxic thresholds for the Brennan’s and Wilson’s paddock sites (Figure 1; July 2005 Progress Report).

The plot numbering for the metals trial started at 49 from the top left of the diagram. The only differences to the methods manual was that the highest Zn and Cu treatment (plot 49 and 50) were reversed on both sites. In addition there were a few minor alterations in the

order of the cadmium treatments as given in Table 4. All changes were updated on the national database.

Table 4. Revised plot numbers for cadmium treatments for both the Wilson's and Brennan's sites

Plot	Treatment	Replicate	Metal rate (mg/kg)
88	Cd 0	1	0
96	Cd 0	2	0
65	Cd 0	3	0
73	Cd 1	1	0.06
64	Cd 1	2	0.06
81	Cd 1	3	0.06
57	Cd 2	1	0.14
80	Cd 2	2	0.14
97	Cd 2	3	0.14
72	Cd 3	1	0.36
63	Cd 3	2	0.36
82	Cd 3	3	0.36
56	Cd 4	1	0.9
79	Cd 4	2	0.9
98	Cd 4	3	0.9

Biosolids trials

There were a total of 16 treatments in the biosolids experiment. This consisted of two biosolids products, applied at eight rates. Biosolids were applied to the soil surface at rates based on the Nitrogen Limited Biosolids Application Rate (NLBAR), which enabled the standardisation of treatments across all sites involved in the National Biosolids Research Program. The rates of application used for the both biosolids products treatments were equivalent to 0, 0.5, 1, 1.5, 3 and 4.5 x NLBAR applied at the start of the experiment. In addition there was a treatment with an annual application of 1.5xNLBAR applied for three consecutive years. There was also one fertiliser control using 100 kg/ha di-ammonium phosphate (DAP) top-dressed (TD) at seeding plus 100 kg/ha urea applied post sowing (i.e. supply 64 kg N/ha and 20 kg P/ha), applied annually for three consecutive years. There were three replications of each treatment set out in a randomised block design. The plot numbering commenced at number one from the top left-hand corner.

Table 5. Chemical analysis of Woodman Point WWTP and Beenyup WWTP biosolids used over three years of the study.

Data on dry weight basis	2003		2004		2005	
	Woodman Point	Beenyup	Woodman Point	Beenyup	Woodman Point	Beenyup
Contaminant (mg/kg)						
Al			3750.0	3450.0	4540.5	4563.6
As	2.9	2.5	3.4	2.4	2.5	2.4
Cd	2.0	1.4	2.0	1.5	2.0	1.5
Cr	123.3	54.0	83.0	122.0	63.7	83.4
Cu	1503.4	1171.0	1266.0	1043.0	1354.8	1093.9
Pb	50.4	36.9	50.0	36.0	60.7	43.3
Hg	1.9	1.7	1.9	2.1	2.2	2.4
Mo	15.8	7.0	22.5	10.5	21.3	10.9
Ni	45.0	33.0	59.0	43.5	42.2	47.8
Se	4.4	4.3	4.0	3.5	5.0	4.4
Zn	900.2	616.0	949.0	630.5	874.8	724.1
DDD/DDE/DDT	0.03	0.04	0.01	0.01	0.02	0.01
Aldrin	0.20	0.02	0.01	0.01	0.01	0.01
Dieldrin	0.90	0.10	0.01	0.01	0.02	0.01
Chlordane	0.30	0.03	0.01	0.01	0.01	0.01
Heptachlor	0.20	0.02	0.01	0.01	0.01	0.01
HCB	0.20	0.02	0.01	0.01	0.01	0.01
Lindane	0.20	0.02	0.01	0.01	0.01	0.01
PCB	0.20	0.20	0.20	0.20	0.20	0.20
Nutrients & other parameters						
TKN (%)	5.78 (4.45)	5.51 (4.4)	4.35 (5.85)	4.90 (5.85)	5.5 (5.9)	6.3 (5.9)
(Nitrate + nitrite) N (mg/kg)	11 (1.13)	27 (1.45)	1.59 (1.05)	0.9 (1.1)	0.55 (0.2)	0.2 (0.2)
Ammonium N (mg/kg)	6108 (1875)	5705 (1125)	2075 (2400)	1400 (2300)	2050 (2950)	1533 (3450)
Total P (%)	1.5 (1.3)	1.99 (2.0)	2.13 (2.7)	3.2 (2.9)	1.31 (1.85)	1.95 (1.85)
Total K (%)			0.70	0.97	0.52 (0.84)	0.34 (0.45)
Total S (%)					1.36 (1.06)	1.09 (0.91)
Total Ca (%)			1.65	2.7	1.74	2.62
pH (H ₂ O?)	7.6	7.6	7.9 (8.4)	9.9 (8.4)	8.1 (7.9)	7.96 (8.0)
solids (%)	18.2	14.2	17.1 (18)	17.9 (16)	18.7 (20)	18.3 (18.5)
Thermotolerant coliforms						
(pathogenic indicator) MPN/g	4.72E+05	6.11E+03	8.15E+05	2.58E+05	1.77E+06	1.89E+06

For nutrient data, figures in parenthesis were actuals for the day otherwise the values are based on long term averages leading up to spreading date.

Crop establishment

The crop rotation selected consisted of a wheat/canola rotation. A complete summary for each site for crop establishment, time of seeding and biosolids application is given in Table 6. The variety of wheat (*Triticum aestivum*) used throughout the experiment was Calingiri and the variety of canola (*Brassica napus*) used was Surpass TT (triazine tolerant).

Table 6. Summary of sowing dates, biosolid and fertiliser application and chemicals applied from 2003 to 2005.

	Brennan's site	Wilson's site
Year and record of activity		
2002		
Site preparation	Lupins grown, 2 t/ha of lime applied and ploughed 4 April 2003	Wheat cut for hay due to ryegrass resistance and ploughed April 2003
2003		
Pre-sowing weed control	1 July: 1 L/ha Bromicide	14 May: 1 L/ha Roundup + 1 L/ha Simazine + 1 L/ha Atrazine
Biosolids and metal application and incorporation	5 May: Biosolids applied & 13 May: incorporated. 6 May: Metals applied & 13 May: incorporated	7 May: Biosolids applied & 14 May: incorporated. 8 May: Metals applied & 14 May: incorporated
Seeding	14 May: 57 kg/ha Calingiri wheat with disc drill	20 May: 8 kg/ha Surpass 501 canola TD then disc drill
Plant counts & 8 week DM		
Post sowing weed control		25 May: 2 L/ha Atrazine + 500 mL/ha Endosulfan
Inorganic fertiliser control treatment 8	13 May: 100kg/ha DAP TD 19 June: 100kg/ha Urea TD	19 May: 100kg/ha DAP TD 19 June: 100kg/ha Urea TD
Soil T ₀	19 May: 0-10 cm & 13 June soil depth	27 May: 0-10 cm & 13 June soil depth
Harvest cuts T ₁	13 November: Hand harvest	30 October: Hand harvest
Soil T ₁	23 Dec: 0-10 cm & 6 Jan 2005: soil depth	16 Dec: 0-10 cm & 16 Dec: soil depth
2004		
Repeat biosolids application	Treatment 7	Treatment 7
Pre-sowing weed control	18 May: 4 L/ha Atrazine + 1 L/ha Roundup + 100 mL/ha Endosulphan	19 May: 1 L/ha Roundup + 30g/ha Logran + 500 mL/ha Diuron + 100 mL/ha Endosulphan
Seeding	18 May: 9 kg/ha Surpass 501 canola TD then disc drill	31 May: 60 kg/ha Calingiri wheat with disc drill
Plant counts & 8 week DM	9 July: plant counts & 4 Aug: 8 week DM	9 July: plant counts & 11 Aug: 8 week DM
Fertiliser control	18 May: 100 kg/ha DAP TD to all metals & T8 biosolids	31 May: 100 kg/ha DAP TD to all metals & T8 biosolids
Post sowing herbicide/fungicide control	23 July: 150 mL/ha Fusilade + wetter	23 July: 1 L/ha Triad fungicide
Harvest	11 Nov: Hand harvest	24 Nov: Hand harvest

Soil T ₂	18 Nov: 0-10 cm and 28 July bulk density	9 Dec: 0-10 cm & 28 July: bulk density
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2005

Repeat application	biosolids	29 April: Treatment 7	29 April: Treatment 7
Pre-sowing control	weed	20 May: 1.5 L/ha Roundup + 30g/ha Logran + 500 mL/ha Diuron + 100 mL/ha Dimethoate + 100 mL/ha Chloropirifos	23 May: 500 mL/ha Atrazine + 2 L/ha Roundup + 500 mL/ha Chloroprifos + 2 L/ha Simazine
Seeding		20 May: 1.5 L/ha Treflan 23 May: 55 kg/ha Calingiri wheat with disc drill	27 May: 9 kg/ha Surpass 501 canola TD then disc drill
Plant counts & 8 week DM		15 July: plant counts & 10 Aug: 8 week DM	15 July: plant counts & 11 Aug: 8 week DM
Fertiliser control		23 May: 100 kg/ha DAP TD to all metals & T8 biosolids	23 May: 100 kg/ha DAP TD to all metals & T8 biosolids
Post sowing herbicide/fungicide control		7 July: 1.5 L/ha Hoegrass + wetter	7 July: 175 mL Aramo + 1/100 Hasten + 400 mL/ha Atrazine
Soil repeat samples		9 June:	9 June:
Harvest		28 Nov: Hand harvest	15 Nov: Hand harvest
Soil T ₃		2 Dec: 0-10 cm and 10 cm+	9 Dec: 0-10 cm and 10 cm+

Sampling and analysis*Plants*

Early plant growth can be sensitive to excessive soil levels of heavy metals, depending on the bioavailability of these metals. Therefore, plant growth was assessed by measuring above ground biomass in plants grown on each of the metal treated plots, eight weeks after crop emergence. The relationship between above ground biomass and the soil metal concentrations measured in soil collected immediately after treatment application can be used to estimate soil metal phytotoxicity thresholds for each metal element as described further by Whatmuff et al. (2004), McLaughlin et al. (2003) and Smart et al. (2002). The soil metal concentrations used to calculate the plant growth EC values presented here were determined by CSIRO prior to crop establishment (T₀) and are therefore only approximate.

The effects on plant growth by the addition of nutrients and heavy metals with either the metal-salts or biosolids were assessed twice during the growing season. Firstly, plant biomass was measured eight weeks after germination and secondly, the amount of grain production and above ground dry matter was measured at harvest. Sub-samples of the grain collected at harvest were sent to collaborators for heavy metal and nutrient analysis. A visual assessment of plant growth on the metal-salt plots was made prior to grain harvest and was used to increase the sampling frequency from specific plots where phytotoxicity (to Cu and Zn), or reduced yield was occurring. Therefore, duplicate samples were taken from these specific plots, instead of single samples as it was thought that the data from the duplicate sampling would improve the assessment of subsequent metal phytotoxicity thresholds (Whatmuff et al. 2004) for the 2003 and 2004 seasons. The data for the duplicate sampling is presented on the national database and is not presented here.

Soils

All surface composite samples (0 - 10 cm) were taken from each plot immediately following treatment application (T_0 July 2003), following the harvest of the first crop (T_1 December 2003), second crop (T_2 December 2004) and the third crop (T_3 December 2005). Soil samples collected during the T_2 harvest and T_3 harvest in metal plots were taken from under each row of sampled plants in the same duplicate pattern described above. All sample preparation and laboratory procedures followed standard protocols (Smart et al. 2002).

All soils were dispatched to collaborators for extraction of bioavailable metals using both 0.01 M calcium chloride and 1 M ammonium nitrate, total soil metal and nutrient elements, soil solution analysis and soil microbial responses. The results of the T_0 earthworm toxicity tests have been reported on soils from NBRP sites in Victoria and Western Australia by McLaughlin et al. (2002) and Whatmuff et al. (2004) and were summarised in the Feb 2005 Progress Report, p 23.





	
<p>Plate 1. Metal-salts trial showing the highest rate of zinc (foreground) and copper (behind) on the Brennan's paddock site, May 2003.</p>	<p>Plate 2. Hand spreading biosolids from the trailer to each 9x4 m plot using shovels and hoes on the Wilson's paddock site, May 2003.</p>
	
<p>Plate 3. Measuring out biosolids for each plot in the biosolids trial using a front-end loader and trailer mounted on electronic load-bars, May 2003.</p>	<p>Plate 4. Biosolids on completion of spreading highlighting the differences in rates used from 0.5xNLBAR to 4.5xNLBAR, May 2003.</p>



Plate 5. Wheat crop grown on the Wilson's site in July 2004 showing the effect of different rates of biosolids and fertiliser treatments.



Plate 6. Harvesting canola on the Brennan's site, November 2004.



Plate 7. Third repeat application of 1.5xNLBAR Woodman Point biosolids spread on the Brennan's site in May 2005.





Plate 8. Establishment of wheat in freshly applied biosolids applied at 1.5xNLBAR (repeat) on the Brennan's site at 8 weeks after sowing in July 2005



Plate 9. Loading up the final (T3) canola harvest (November 2005) on the Wilson's site.



Plate 10. Metals salt trial showing the toxic effect on wheat growth in the highest rate of zinc (foreground) in July 2005, three years after initial application.



	
<p>Plate 11. Poor growth of wheat grown on the control treatment (nil fertiliser) on the Brennan's site at harvest in November 2005</p>	<p>Plate 12. Growth of wheat in the repeat 1.5xNLBAR on the Brennan's site at harvest in November 2005 (contrast with Plate 5 opposite).</p>

Additional experimentation

Lime-amended biosolids

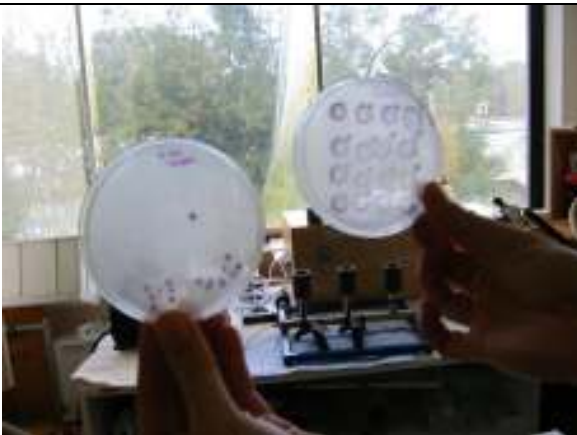

Lime-amended biosolids, not included in the original field experiment, were examined further as a pilot study at a site at Wongamine commencing in 2005. The trial consisted of nine treatments comprising: three rates of LAB at 0.5xNLBAR, 1xNLBAR and 1.5xNLBAR (equivalent to dry t/ha); one rate of dewatered biosolids cake (DWC) at 1xNLBAR; four rates of lime at 0 t/ha, 2.3 t/ha, 4.6 t/ha and 6.9 t/ha (each with a basal fertiliser dressing of 100 kg urea/ha and 100 kg di-ammonium phosphate/ha); and a control (nil fertiliser). The experiment was arranged in a completely randomised block design with three replicates on a red-brown sandy loam. Shoot dry matter production at maximum growth (anthesis) and grain yield were measured for wheat (*Triticum aestivum*) as an indicator of nutrient availability.

Soil bicarbonate extractable P was increased by the addition of biosolids more so than LAB at comparable N loadings. However, it would be expected that P availability would be similar when biosolids/LAB were applied at comparable P loading rates. Wheat dry matter production in the field trial indicate a yield response to increasing rates of LAB, with the 4 dry t/ha most similar to the district fertiliser practice and no yield response below the 4 dry t/ha. This paper will include discussion of the grain results following the 2003 harvest. The results of this study will provide agronomic field data to better calculate land application rates of LAB, combined with laboratory data to better understand their role in crop N and P nutrition.

	
<p>Plate 13. Comparison of pH and nutrient responses in wheat to application of lime-amended biosolids (RHS) and biosolids (LHS) at Wongamine, June 2005</p>	<p>Plate 14. Wheat grown in lime-amended biosolids at harvest in December 2005 showing evidence of remnants of biosolids.</p>

Pathogens research

Western Australia has been instrumental in pathogen research, following the land application of biosolids in Australia. A pilot study within this project funded a Curtin student to conduct research in conjunction with CSIRO, Floreat (Crute 2005). Following completion of her honours project, Crute (now Schwarz) was awarded an Australian Postgraduate Award (APA) to further her research in the pathogen field, the project being funded by the Cooperative Research Centre for Water Quality and Treatment (CRCWQT), the Water Corporation and the Victorian Department of Human Services. Pathogens being examined include *Salmonella* spp., *E.coli*, bacteriophage, Adenovirus and cryptosporidium. This project forms part of a larger project, which includes two other PhD students studying persistent organic pollutants and non-organochlorine pesticides, pharmaceuticals, personal care products and endocrine disruptors.

	
<p>Plate 15. Bacteriophage samples collected from soil sampled on the pathogen experimental site, CSIRO laboratory, Floreat, 2004.</p>	<p>Plate 16. Spreading of biosolids for Karen Crute's pathogen survival research at Wongamine, June 2004.</p>

Research Results and Discussion

Metal salt experiment

Concentrations of Cd, Cu and Zn in the soil were measured immediately following the application of the metal-salts to the trial sites (T_0) and then after each harvest for three subsequent years (T_1 , T_2 and T_3). Background metal levels at both the Brennan and Wilson's paddock sites were initially low (0.10 mg/kg Cd, 5 to 8 mg/kg Cu and 6 to 45 mg/kg Zn). These were compared with the Maximum Allowable Soil Contaminant Concentrations (MACC) (DEP, WRC & DOH 2002) to allow the range of contaminant values in biosolids is to be reviewed following the outcomes from the NBRP project (NRMMC, 2004). They are presented separately for each metal over the three years as follows.

Cadmium

Increasing levels of Cd is not expected to significantly affect plant growth or grain yield. The problem with Cd is that it bio-accumulates in the food chain affecting human health and is measured primarily as grain Cd concentrations. The basis for Cd salt addition was to achieve a target soil solution concentration that would result in excessive Cd accumulation in the wheat grain. Soil Cd concentrations over the three years of the experiment for both sites are presented in Table 7. Soil Cd levels were raised to a maximum of 1.157 mg/kg on the Brennan's paddock site (T_2) and 2.03 mg/kg Cd on the Wilson's paddock site (T_2). The current national MACC for Cd of 1 mg/kg was exceeded, but not the Western Australian guidelines of 3 mg Cd/kg (DEP, WRC & DOH 2002). This enabled the resultant uptake of Cd in grain samples of wheat and canola to be investigated.

The measured metal Cd concentration values at (T_0) were less than the proposed target values at both sites, which would be expected given that soil sampling occurred immediately after application. Soil measurements collected after the first harvest (T_1) provided a more realistic result as subsequent cultivations used for crop establishment and weed control would have further mixed the metals throughout the soil profile. The concentration of Cd in the soil for any given treatment generally increased over the duration of the experiment.

Table 7. Target and measured soil metal concentrations for cadmium in the metal-salt experiment in the surface 0-10 cm depth at the Gillingarra sites over four sampling periods (T₀, T₁, T₂ and T₃).

Site		Brennan's (mg/kg)			
Year		2003	2003	2004	2005
Time		T0	T1	T2	T3
Treatment	Rate Cd (mg/kg)				
0	0	0.029	0.033	0.040	0.047
1	0.06	0.072	0.097	0.120	0.147
2	0.14	0.124	0.187	0.273	0.230
3	0.36	0.280	0.493*	0.430*	0.390*
4	0.9	0.673	0.873*	1.157*	1.090*
<i>Mean</i>		<i>0.235</i>	<i>0.337</i>	<i>0.404</i>	<i>0.381</i>
Lsd (p=0.05)			0.352	0.384	0.237

Site		Wilson's (mg/kg)			
Cadmium treatment	Rate Cd (mg/kg)				
0	0	0.020	0.107	0.120	0.117
1	0.06	0.050	0.163	0.243	0.240
2	0.14	0.038	0.413	0.430	0.490*
3	0.36	0.277	0.733	1.050*	0.603*
4	0.9	0.172	1.897*	2.030*	1.673*
<i>Mean</i>		<i>0.112</i>	<i>0.663</i>	<i>0.775</i>	<i>0.625</i>
Lsd (p=0.05)			0.692	0.347	0.243

¹ Maximum Allowable Soil Contaminant Concentration for agricultural lands from NSW EPA (1997) =1.0 mg Cd/kg, and 3.0 mg Cd/kg (DEP, WRC & DOH 2002).

Plant growth

As expected, residual levels of Cd did not affect any plant growth or yield parameters measured over the three years of the experiment on either site (Table 8; $p > 0.05$). The T3 data has been presented in full for this report only, with more detailed information on T1 and T2 results provided in the Feb 2006 progress report.

Table 8. Mean wheat shoot dry matter sampled eight weeks after seedling emergence, harvest grain yield and above ground dry matter on the Gillingarra sites from 2003 to 2005.

2003 – Brennan's wheat						
Treatment	Rate Cd (mg/kg)	Plants/m ²	20 plants (g)	Harvest wt (t/ha)	dry Harvest yield (t/ha)	100 seed wt (g)
<i>Mean</i>		97	22.8	7.63	3.23	4.18
I.s.d. (p=0.05)		ns	ns	ns	ns	ns

2003 Wilson's-canola						
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Treat No	Rate Cd (mg/kg)	Plants/m ²	20 plants (g)	Harvest dry wt (t/ha)	Harvest yield (t/ha)	100 seed wt (g)
<i>Mean</i>		148.8	21.14	4.37	1.94	0.365
Lsd (p=0.05)		ns	ns	ns	ns	ns
2004 Brennan's-canola						
Treatment	Rate Cd mg/kg	Plants/m ²	20 plants (g)	Harvest wt (t/ha)	dry Harvest yield (t/ha)	100 seed wt (g)
<i>Mean</i>		74.3	14.6	1.91	0.93	0.35
I.s.d. (p=0.05)		ns	ns	ns	ns	ns
2004 Wilson's-wheat						
Treat No	Rate Cd (mg/kg)	plants/m ²	20 plants (g)	Harvest wt (t/ha)	dry Harvest yield (t/ha)	100seed wt (g)
<i>Mean</i>		158.1	7.6	6.85	3.67	2.99
Lsd (p=0.05)		ns	ns	ns	ns	ns
2005 Brennan's-wheat						
Treat No	Rate Cd (mg/kg)	plants/m ²	20 plants (g)	Harvest wt (t/ha)	dry Harvest yield (t/ha)	100seed wt (g)
0	0	75.2	8.7	2.04	0.93	4.12
1	0.06	72.7	11.3	2.53	1.19	4.58
2	0.14	77.6	8.5	3.23	1.54	4.27
3	0.36	80.7	8.1	2.87	1.38	4.37
4	0.9	68.4	11.0	3.38	1.57	4.10
<i>Mean</i>		74.9	9.5	2.81	1.32	4.29
Lsd (p=0.05)		ns	ns	ns	ns	ns
2005 Wilson's-canola						
Treat No	Rate Cd (mg/kg)	plants/m ²	20 plants (g)	Harvest wt (t/ha)	dry Harvest yield (t/ha)	100seed wt (g)
0	0	56.8	16.9	4.52	1.40	0.359
1	0.06	68.4	14.2	3.62	1.25	0.367
2	0.14	66.6	12.1	2.44	0.85	0.355
3	0.36	75.2	13.5	2.74	0.98	0.371
4	0.9	62.9	13.2	4.32	1.46	0.321
<i>Mean</i>		66.0	14.0	3.53	1.19	0.355
Lsd (p=0.05)		ns	ns	ns	ns	ns

Grain Cd concentrations

Concentrations of Cd in the grain of wheat and canola were increased significantly as application rates increased above 0.14 mg Cd/kg on the Brennan's site and 0.36 mg Cd/kg on the Wilson's site ($p < 0.05$), respectively, over the three years (Table 9). The highest mean Cd value recorded in grain was 0.29 mg/kg in wheat at T1 for Cd application rates of 0.90 mg/kg on the Brennan's site ($p > 0.05$). The uptake of Cd by grain generally decreased over time from T1 to T3. As the concentration of total Cd measured in the soil generally increased over time, it would be expected that grain concentrations would follow a similar pattern. This result, however, was in contrast to what was measured in the soil, and it is likely that the solubility and bioavailability of Cd decreased over time, possibly due to reactions with the soil rendering Cd less available for plant uptake.

Table 9. The effect of increasing total soil Cd concentrations on Cd concentrations of harvested grain for the Brennan and Wilson's sites over three years for three consecutive crops.

Site		Brennan's		
Year		2003	2004	2005
Crop		Wheat	Canola	Wheat
Cadmium treatment	Rate Cd (mg/kg)	Cd conc. in grain (mg/kg)	Cd conc. in grain (mg/kg)	Cd conc. in grain (mg/kg)
0	0	0.020	0.027	0.050
1	0.06	0.037	0.033	0.057
2	0.14	0.090*	0.057*	0.080*
3	0.36	0.193*	0.070*	0.100*
4	0.9	0.297*	0.147*	0.167*
<i>Mean</i>		<i>0.127</i>	<i>0.073</i>	<i>0.091</i>
Lsd ($p=0.05$)		0.064	0.027	0.023

Site		Wilson's		
Year		2003	2004	2005
Crop		Canola	Wheat	Canola
Cadmium treatment	Rate Cd (mg/kg)	Cd conc. in grain (mg/kg)	Cd conc. in grain (mg/kg)	Cd conc. in grain (mg/kg)
0	0	0.020	0.020	0.063
1	0.06	0.043	0.040	0.073
2	0.14	0.043	0.043	0.087
3	0.36	0.070*	0.153*	0.130*
4	0.9	0.123*	0.167*	0.187*
<i>Mean</i>		<i>0.060</i>	<i>0.085</i>	<i>0.108</i>
Lsd ($p=0.05$)		0.064	0.053	0.037

Included also are the l.s.d. values for each growth parameter following analysis of variance at $p=0.05$. Treatments with * are significantly different from the control. NLBAR = nitrogen limiting biosolids application rate. Please note that the Cd rates in the July 2005 report may be different and are not the correct values due to a miscalculation in the Cd plot layout.

When the concentrations of Cd in the grain of wheat are plotted against total Cd measured in the soil, there is a linear and increasing relationship. For example, Figure 3 shows the uptake of Cd in the grain of wheat plants measured at the Wilson's site in the second year plotted against the Cd concentration in the soil at harvest (T1), as illustrated by Mark Whatmuff. Overall the slope of the uptake of Cd in the Western Australian sites was reported to be typically less than that occurring in the other Australian sites.

In the work by McLaughlin et al. (2006), Cd has been investigated in detail over a range of soil types throughout Australia. A partition coefficient (K_d) was determined to describe Cd distribution between soil and pore water and a bioconcentration factor (BCF) determined for wheat grain by dividing grain Cd concentration by soil Cd concentration, which is discussed further in that paper. The K_d and BCF were used to estimate critical soil guideline values on a range of soil types to ensure that grain Cd in wheat not exceed 0.1 mg/kg. The implications of Cd uptake following the land application of biosolids are discussed further in that section.

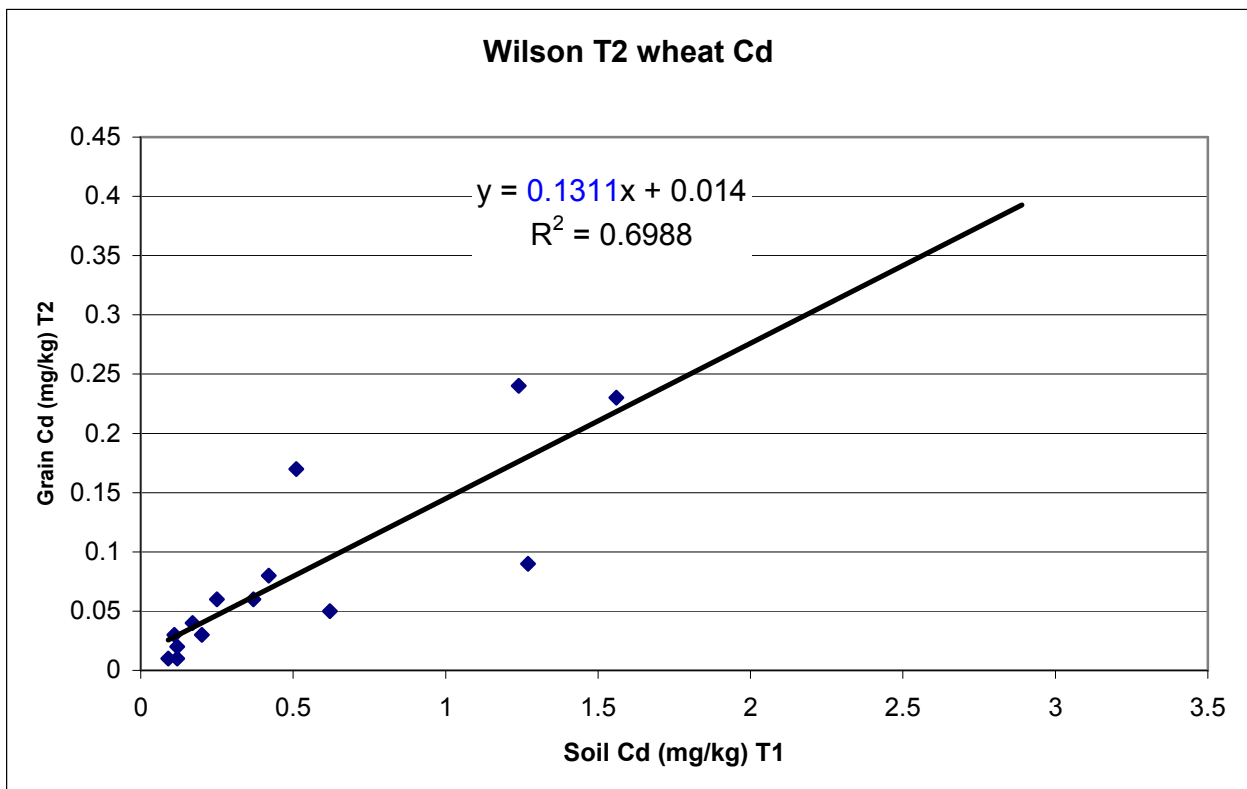


Figure 3. Relationship between total soil Cd (T1) and the concentration of Cd in the grain of wheat at harvest (T2) on the Wilson's site (from Whatmuff,2006)

Copper

The rates of Cu metal-salts were calculated to raise soil Cu concentrations in the highest treatments to levels above the MACC (100 mg/kg for Cu), as consistent with Whatmuff and others (2004). The high rate treatments were designed to exceed phytotoxicity thresholds for wheat plants (McLaughlin et al. 2003) (i.e. plant toxicity or reduced yield). There were 11 application rates of Cu, with the EC₅₀ value for wheat seedlings consistent with rate 9. Plant results are discussed in more detail under yield responses.

The concentrations of Cu increased with increasing application rates, as would be expected ($P < 0.05$) over all sampling events (Table 10). In general, the concentrations of Cu increased over time, being higher than the target rate applied, which was more noticeable on the Wilson's site. The higher concentrations of metal salts were likely due to the removal of a large percentage of stones in the topsoil during sieving, thereby concentrating the Cu in the soil sampled for analysis. There were some problems with the large size of the Cu salt, which posed problems during routine sieving of stone removal prior to chemical analysis, however this was overcome with careful preparation using a brush mill grinder.

In the first year of growth on the Brennan's site, the growth of wheat and yield was reduced at the highest level of Cu only (936 mg Cu/kg, Table 11). The response to increasing levels of Cu was more pronounced for canola growth and yield on the Wilson's paddock at the two highest rates of Cu (> 1022 mg Cu/kg).

In the second year, the canola grown on the Brennan's site showed no reduction in plant growth and yield with increasing levels of residual Cu applied up to 936 kg/ha compared with the control (Table 11; $p > 0.05$). The wheat grown in increasing rates of Cu on the Wilson's site showed a 50% reduction in shoot dry matter at 8 weeks after planting at application rates > 101 kg Cu/ha. Over the growing season, differences in the growth of wheat became less apparent so that by harvest, grain yields wheat plants were 50% less than that of the control at application rates $> 1,000$ mg Cu/kg.

The final year (T3) was the most interesting in terms of the plant response to concentrations of residual copper. The grain yield of canola on the Wilson's site was reduced significantly at target concentrations of 151 mg Cu/kg (Table 11; $p < 0.05$). It is assumed that canola is more sensitive to Cu than wheat and given that EC₅₀ values were determined by wheat bioassay, it is probable.

Table 10. Target and measured soil metal concentrations for copper in the metal-salt experiment over three years in the surface 0-10 cm depth at the two Gillingarra sites.

Cu (mg/kg)					
Brennan's paddock					
Trt #	Applied	T0	T1	T2	T3
0	0	5	10	3	8
1	9	5	7	5	20
2	14	5	5	9	10
3	21	10	21	13	24
4	31	6	9	36	39
5	46	18	32	31	42
6	69	11	92	56	185*
7	104	147	57	112	127*
8	156	449	80	115	276*
9	234	264	60	244	270*
10	468	640	406*	474*	872*
11	936	224	418*	653*	577*
Lsd (P=0.05)		ns	232.3	270.4	65.2
Cu (mg/kg)					
Wilson's paddock					
Trt #	Applied	T0	T1	T2	T3
0	0	8	14	12	10
1	20	10	22	31	29
2	30	38	16	43	63
3	45	69	63	90	187
4	67	181	62	210	345
5	101	61	120	116	118
6	151	401	224	669	432
7	227	541	489	529	427
8	341	832	399	825	1285
9	511	2415*	648	520	1048
10	1022	2210*	1255*	1266	2640*
11	2044	2957*	2485*	2950*	2135*
Lsd (P=0.05)		1299	967.2	1597.8	1407.1
MACC ¹				100 mg/kg	

Table 11. The effect of increasing rates of copper on mean plant growth parameters on two sites over three years

Brennans Wheat T1						
Treat No	Rate Cu (g/kg)	plants/m ²	20 plants (g)	Harvest dry wt (t/ha)	Harvest yield (t/ha)	100 seed wt (g)
0	0	98.1	22.26	7.95	3.34	3.98
1	9	89.8	22	8.06	3.52	4.34
2	14	100.9	24.75	9.1	4.02	4.47
3	21	93.5	27.15	8.52	3.74	4.37
4	31	130.6	21.62	7.98	3.46	4.34
5	46	114.8	22.78	7.79	2.88	4.35
6	69	113	21.83	8.11	3.58	4.09
7	104	85.2	24.88	6.47	2.73	4.14
8	156	123.2	21.42	9.68	4.20	4.11
9	234	101.9	21.5	8.82	3.80	3.98
10	468	93.5	29.22	7.45	3.32	3.99
11	936	81.5	10.96	4.58	1.96	3.88
<i>Mean</i>		<i>102.2</i>	<i>22.53</i>	<i>7.87</i>	<i>3.38</i>	<i>4.17</i>
Lsd (p=0.05)		ns	ns	ns	ns	ns

Wilson's canola T1						
Treat No	Rate Cu (mg/kg)	plants/m ²	20 plants (g)	Harvest dry wt (t/ha)	Harvest yield (t/ha)	100 seed wt (g)
0	0	162	16.5	4.18	1.86	0.38
1	20	142.6	24.2	4.21	1.93	0.36
2	30	121.3	16.8	4.21	1.81	0.365
3	45	144.4	22.6	4.61	2.13	0.415
4	67	143.5	20.7	3.53	1.31	0.365
5	101	114.8	22.3	3.58	1.52	0.35
6	151	139.8	15.4	4.1	1.86	0.355
7	227	126.9	21.6	4.25	1.89	0.37
8	341	97.2	8.9	2.86	1.40	0.38
9	511	78.7	17.4	5.21	1.84	0.365
10	1022	43.5	3.4	2.42	0.98	0.37
11	2044	19.4	0	1.19	0.49	0.35
<i>mean</i>		<i>111.2</i>	<i>15.8</i>	<i>3.69</i>	<i>1.58</i>	<i>0.369</i>
Lsd (p=0.05)		ns	12.49	1.81	ns	ns

Brennan's canola T2

Treat No	Rate Cu mg/kg	plants/m ²	20 plants (g)	Harvest dry wt (t/ha)	Harvest yield (t/ha)	100 seed wt (g)
0	0	70.8	15.2	2.11	1.07	0.36
1	9	111.1	13.7	0.76	0.95	0.33
2	14	102.8	20.1	2.30	1.15	0.33
3	21	116.7	17.2	1.78	0.79	0.39
4	31	81.9	20.4	2.50	1.29	0.37
5	46	93.1	14.7	2.15	0.95	0.36
6	69	80.6	17.5	1.79	1.00	0.38
7	104	58.3	17.2	2.26	1.01	0.40*
8	156	79.2	19.3	1.62	0.83	0.38
9	234	65.3	17.3	2.21	1.08	0.39
10	468	84.7	17.8	2.32	1.02	0.36
11	936	11.1	2.6	2.72	1.29	0.35
<i>mean</i>		79.6	16.1	2.04	1.04	0.36
Lsd (p=0.05)		ns	ns	ns	ns	0.039

Wilson's wheat T2

Treat No	Rate Cu (mg/kg)	plants/m ²	20 plants (g)	Harvest dry wt (t/ha)	Harvest yield (t/ha)	100seed wt (g)
0	0	136.1	10.2	6.73	2.58	3.41
1	20	144.4	11.0	8.54	3.83	3.71
2	30	151.4	9.2	7.11	2.58	3.55
3	45	152.8	7.1	7.05	2.96	3.68
4	67	154.2	9.7	8.02	3.40	3.67
5	101	158.3	5.1*	7.03	2.72	3.68
6	151	183.3	5.5*	7.95	3.21	3.66
7	227	143.1	3.5*	4.96	2.14	3.76
8	341	119.4	3.0*	4.44	2.15	3.49
9	511	133.3	4.0*	5.47	2.28	3.51
10	1022	113.9	1.1*	2.93*	1.53	3.81
11	2044	86.1	0.7*	1.95*	0.94*	4.01
<i>mean</i>		140	5.9	3.23	2.53	3.66
Lsd (p=0.05)		ns	4.4	2.18	1.60	ns

Brennan's Wheat T3

Treat No	Rate Cu (mg/kg)	plants/m ²	20 plants (g)	Harvest dry wt (t/ha)	Harvest yield (t/ha)	100seed wt (g)
0	0	68.8	7.5	2.64	1.20	4.46
1	20	77.9	9.4	3.78	1.91	4.47
2	30	75.2	10.6	3.48	1.72	4.49
3	45	78.8	6.2	3.65	1.81	4.44
4	67	70.6	7.5	2.94	1.43	4.56
5	101	72.4	9.6	1.79	1.03	4.23
6	151	66.9	8.6	2.58	1.32	4.62
7	227	68.8	8.9	3.12	1.53	4.55
8	341	63.2	13.6*	3.32	1.56	4.33
9	511	66.9	9.7	2.44	1.27	4.63
10	1022	66.0	12.4*	2.78	1.33	4.37
11	2044	62.3	0.6	0	0*	0*
<i>mean</i>		69.8	8.7	2.71	1.34	4.10
Lsd (p=0.05)		ns	4.24	ns	0.876	0.756

Wilson's Canola T3

Treat No	Rate Cu (mg/kg)	plants/m ²	20 plants (g)	Harvest dry wt (t/ha)	Harvest yield (t/ha)	100seed wt (g)
0	0	50.4	12.7	4.18	1.43	0.358
1	20	53.2	13.4	4.53	1.30	0.353
2	30	70.6	13.2	3.20	1.11	0.354
3	45	60.5	13.8	4.06	1.36	0.385
4	67	64.2	13.5	4.04	1.35	0.359
5	101	44.0	10.8	2.78	0.96	0.347
6	151	31.2	4.7	1.35	0.49	0.393
7	227	24.8	3.6	1.24	0.43	0.388
8	341	16.5	5.2	0.64	0.25	0.410
9	511	11.0	0.0	0.97	0.27	0.395
10	1022	1.8	0.0	0.64	0.21	0.371
11	2044	0.9	0.0	0.00	0.00	0.000
<i>mean</i>		35.8	7.59	2.3	0.76	0.343
Lsd (p=0.05)		31.54	7.92	1.95	0.68	0.050

Metal uptake in grain

On the Brennan's site the concentration of Cu in wheat grain was increased significantly at Cu application rates greater than 234 mg Cu/kg in the first year (T1) (Table 12; $p < 0.05$), but was not increased in canola grain in the following year. In the third year, application rates above 468 mg Cu/kg resulted in significantly higher grain Cu ($p < 0.05$). A similar trend was observed on the Wilson's site with increases in concentrations of Cu measured in canola grain at application rates greater than 341 mg Cu/kg ($p < 0.05$) in the first and third year in canola grain. In the second year, there was little relationship between the level of applied Cu and the concentration of Cu in wheat grain.

Table 12. The effect of increasing total soil Cu concentrations on Cu concentrations of harvested grain for the Brennan and Wilson's sites over three years for three consecutive crops.

Site		Brennan's		
Year		2003	2004	2005
Crop		Wheat	Canola	Wheat
Copper treatment	Rate Cu (mg/kg)	Cu conc. in grain (mg/kg)	Cu conc. in grain (mg/kg)	Cu conc. in grain (mg/kg)
0	0	2.60	2.90	2.70
1	9	3.40	2.20	3.85
2	14	2.80	2.50	3.25
3	21	3.15	2.15	3.55
4	31	3.65	2.45	3.40
5	46	3.10	2.45	3.20
6	69	3.55	2.80	3.60
7	104	3.55	2.95	3.75
8	156	3.40	2.90	4.00
9	234	3.85*	3.30	4.35
10	468	4.40*	3.75	5.70*
11	936	4.90*	3.65	*
<i>Mean</i>		3.53	2.83	3.76
Lsd ($p=0.05$)		1.065	ns	1.713

Site		Wilson's		
Year		2003	2004	2005
Crop		Canola	Wheat	Canola
Copper treatment	Rate Cu (mg/kg)	Cu conc. in grain (mg/kg)	Cu conc. in grain (mg/kg)	Cu conc. in grain (mg/kg)
0	0	2.65	4.10	2.70
1	20	2.45	4.60	3.00
2	30	2.85	4.45	2.78
3	45	2.80	3.55	2.75
4	67	3.20	2.80	3.50
5	101	2.80	4.00	3.05
6	151	3.45	2.60	4.05*
7	227	3.25	2.90	3.10
8	341	4.00*	2.80	4.35*
9	511	3.85*	3.50	4.40*
10	1022	3.95*	2.85	4.15*
11	2044	4.75*	4.75	*
<i>Mean</i>		3.33	3.57	3.44
Lsd (p=0.05)		0.81	1.39	1.043

Included also are the l.s.d. values for each growth parameter following analysis of variance at p=0.05. Treatments with * are significantly different from the control. NLBAR = nitrogen limiting biosolids application rate. No values indicate that plants had reached the toxic threshold.

Zinc

The addition of the Zn metal-salts raised soil Zn concentrations in the highest treatments (Table 13) to levels above the MACC (200 mg/kg Zn). The target concentrations of metals in the two highest metals rates at both sites were not achieved, and in contrast to the Cu-salts, although the reasons are unknown. The Zn salt applied was fine and perhaps there was loss of powder through wind erosion during dry, windy conditions or leaching below the 10cm depth, which needs to be investigated further.

Table 13. Target and measured soil metal concentrations for zinc in the metal-salt experiment over three years in the surface 0-10 cm depth at the two Gillingarra sites.

Brennan's Zn (mg/kg)					
Trt #	Applied	T0	T1	T2	T3
0	0	6	9	9	10
1	14	16	21	30	20
2	21	21	20	40	26
3	32	22	42	46	58
4	48	25	46	60	56
5	72	43	94	108*	77
6	108	155	110	91	121
7	161	107	150	131*	190
8	242	169	173	234*	178
9	363	306*	328*	334*	310
10	726	532*	312*	284*	206
11	1452	421*	334*	294*	262*
Lsd (p=0.05)		229.0	170.7	78.5	201.9
Wilson's Zn (mg/kg)					
Trt #	Applied	T0	T1	T2	T3
0	0	45	26	36	35
1	25	52	68	52	40
2	37	59	66	68	52
3	56	56	64	89	102
4	84	81	182	120	142*
5	126	194	148	172*	94
6	189	224	188	250*	277*
7	283	240	196	176*	184*
8	425	507	386	335*	204*
9	637	507	326	292*	255*
10	1274	622	490	495*	325*
11	2548	448	416	340*	272*
Lsd (p=0.05)		268	118.9	88.3	78.8
MACC = 200 mg/kg					

High rates of Zn had a deleterious effect on the growth of wheat and canola, as would be expected (Table 14). In year one (2003), the dry matter yield of wheat on the Brennan's paddock site was significantly reduced ($p < 0.05$) with target levels of Zn greater than 726 mg/kg up to a point where no growth was observed (1452 mg Zn/kg). The canola on the Wilson's paddock site failed to establish at concentrations of Zn greater than 637 mg/kg. A 50% reduction in plant biomass (EC_{50}) at 8 weeks after sowing was measured at soil Zn levels of approximately 189 to 363 mg/kg on the Wilson's and Brennan's sites, respectively. By harvest, grain yield in canola on the Wilson's paddock was more sensitive to soil Zn at comparative concentrations than wheat on the Brennan's site.

In year two (2004), increasing concentrations of Zn resulted in a significant decrease in canola grain yield at target application rates > 242 mg Zn/kg with nil grain harvested on the Brennan's site at > 726 mg Zn/kg. Shoot dry matter of wheat following application rates of > 189 mg Zn/kg on the Wilson's site were significantly reduced compared with the control ($p < 0.05$). Wheat grew poorly on the highest rate of Zn (2,548 mg Zn/kg) yielding 0.46 t/ha compared with the control 1.92 t/ha ($p < 0.05$). In contrast, application rates of Zn of 25 mg/kg increased wheat yields to 3.7 t/ha ($p < 0.05$).

At T3, in the final year (2005), the growth of canola was significantly reduced at target application rates of Zn above 126 mg Zn/kg ($p < 0.05$), with a 50% reduction in plant biomass (EC_{50}) at 8 weeks after sowing measured at target rates of 84 mg Zn/kg. The growth of wheat in T3 was similar to the first year, with application rates of Zn > 726 mg/kg causing a significant reduction in grain yield ($p < 0.05$). Canola was more sensitive to high levels of Zn than wheat over all years and sites.

Table 14. The effect of increasing rates of zinc on mean plant growth parameters on two sites over three years

Brennan's wheat T1						
Treat No	Rate Zn (mg/kg)	plants/m ²	20 plants (g)	Harvest wt (t/ha)	dry Harvest yield (t/ha)	100 seed wt (g)
0	0	102.8	18.0	7.25	3.23	4.19
1	14	99.1	24.9	7.62	3.06	3.91
2	21	101.9	24.3	8.65	3.79	3.73
3	32	116.7	27.0	8.82	3.87	3.96
4	48	94.4	25.3	6.88	2.86	4.07
5	72	95.4	17.5	7.45	3.10	3.82
6	108	91.7	19.6	7.28	2.95	3.97
7	161	84.3	20.6	7.31	3.18	4.05
8	242	61.1	14.4	4.17	1.69	3.67
9	363	44.4*	10.2	4.04	1.66	3.51*
10	726	9.3*	2.4*	0.73*	0.03*	3.54*
11	1452	0*	0*	0*	0*	0*
<i>Mean</i>		75.1	17	5.85	2.47	3.53
Lsd ($p=0.05$)		43.68	13.52	3.96	1.84	0.62

Wilson's canola T1

Treat No	Rate Zn (mg/kg)	plants/m ²	20 plants (g)	Harvest dry wt (t/ha)	Harvest yield (t/ha)	100 seed wt (g)
0	0	134.3	14.4	3.46	1.40	0.345
1	25	121.3	23.1	4.77	2.08	0.380
2	37	136.1	19.5	3.80	1.65	0.380
3	56	118.5	15.2	3.88	1.66	0.385
4	84	47.2*	12.2	1.56*	0.56*	0.395
5	126	39.8*	12.6	2.06*	0.92*	0.390
6	189	13.0*	4.2	0.70*	0.22*	0.390
7	283	20.4*	6.4	0.79*	0.23*	0.150
8	425	3.70*	0*	0.28*	0.16*	0.165
9	637	0*	7.8	0*	0*	0
10	1274	0*	0*	0*	0*	0
11	2548	0*	0*	0*	0*	0
<i>mean</i>		52.9	9.6	1.78	0.74	0.248
Lsd (p=0.05)		26.39	11.66	1.42	0.616	0.211

Brennan's canola T2

Treat No	Rate Zn mg/kg	plants/m ²	20 plants (g)	Harvest wt (t/ha)	dry Harvest yield (t/ha)	100 seed wt (g)
0	0	51.4	15.5	1.93	0.97	0.34
1	14	81.9	17.8	2.82*	1.32	0.37
2	21	81.9	20.3	1.74	0.83	0.37
3	32	94.4*	14.7	1.53	0.77	0.36
4	48	44.4	12.1	2.05	0.65	0.37
5	72	68.1	12.6	1.05*	0.74	0.36
6	108	81.9	13.0	2.75*	1.19	0.39*
7	161	95.8*	11.4	2.12	1.05	0.36
8	242	55.6	10.3	0.55*	0.39*	0.38*
9	363	20.8	12.3	1.38	0.56	0.32
10	726	2.8*	0.0*	0.01*	0*	0
11	1452	0*	0.0*	0.00*	0*	0
<i>mean</i>		56.6	11.7	1.49	0.71	0.3
Lsd (p=0.05)		37.66	7.15	0.78	0.52	0.031

Wilson's wheat T2

Treat No	Rate Zn (mg/kg)	plants/m ²	20 plants (g)	Harvest wt (t/ha)	dry Harvest yield (t/ha)	100seed wt (g)
0	0	183.3	7.21	4.45	1.92	3.25
1	25	159.7	6.29	8.54	3.66*	3.61
2	37	163.9	8.41	6.22	2.81	3.62
3	56	151.4	7.27	6.92	2.69	3.48
4	84	152.8	5.41	5.97	2.30	3.63
5	126	165.3	5.68	4.43	1.80	3.31
6	189	141.7	4.26*	3.17	1.06	3.41
7	283	143.1	2.27*	4.94	2.46	3.64
8	425	145.8	1.61*	3.97	2.08	3.90
9	637	156.9	1.47*	2.82	1.54	3.94
10	1274	162.5	1.44*	1.79	1.21	3.87
11	2548	131.9	0.10*	1.03*	0.46*	3.82
<i>mean</i>		154.9	4.29	4.52	2.00	3.62
Lsd (p=0.05)		ns	2.61	3.24	1.28	ns

Brennan's wheat T3

Treat No	Rate Zn (mg/kg)	plants/m ²	20 plants (g)	Harvest wt (t/ha)	dry Harvest yield (t/ha)	100seed wt (g)
0	0	59.6	8.70	2.77	1.37	4.37
1	14	67.8	11.21	2.94	1.41	4.48
2	21	65.1	7.62	3.99	1.94	4.45
3	32	70.6	11.80	2.80	1.41	4.24
4	48	72.4	8.64	2.83	1.34	4.45
5	72	80.7	12.88	3.98	1.92	4.47
6	108	71.5	7.64	4.04	1.95	4.38
7	161	64.2	7.88	2.23	1.26	4.34
8	242	59.6	2.50*	2.59	1.15	4.13
9	363	65.1	4.84	2.02	0.96	4.29
10	726	71.5	0.30*	0.31*	0.14*	3.03*
11	1452	76.1	0.31*	0*	0*	0*
<i>mean</i>		68.7	7.03	2.54	1.24	3.89
Lsd (p=0.05)		ns	4.576	1.766	0.942	0.571

Wilson's canola T3

Treat No	Rate Zn (mg/kg)	plants/m ²	20 plants (g)	Harvest wt (t/ha)	dry Harvest yield (t/ha)	100seed wt (g)
0	0	61.4	14.41	3.23	1.41	0.390
1	25	50.4	12.39	2.58	0.95	0.394
2	37	59.6	10.08	2.90	0.95	0.358
3	56	48.6	9.45	2.24	0.74	0.386
4	84	29.3*	3.84*	2.93	0.98	0.354
5	126	20.2*	0*	0.78*	0.32*	0.419
6	189	16.5*	0*	0.66*	0.15*	0.348
7	283	0.9*	0*	0.34*	0.09*	0.183*
8	425	10.1*	0*	0*	0*	0
9	637	9.0*	0*	0*	0*	0
10	1274	0.0*	0*	0*	0*	0
11	2548	3.7*	0*	0*	0*	0
<i>mean</i>		25.1	5.21	1.31	0.47	0.236
Lsd (p=0.05)		22.65	4.17	1.91	0.71	0.179

Included also are the l.s.d. values for each growth parameter following analysis of variance at p=0.05.

Metal uptake in grain

Increasing rates of Zn produced variable results in terms of final grain concentration in grain samples (Table 15). The canola tended to accumulate Zn in the grain more than wheat as soil Zn increased, regardless of the paddock site. The concentration of Zn in canola grain reached a maximum of 121 mg /kg in the first year and toxic effects were noted at lower application rates than for wheat. Concentrations of Zn in canola grain was increased significantly above that of the control at application rates greater than 56 mg Zn/kg on the Wilson's site in the first year, 21 mg Zn/kg on the Brennan's site in the second year and 126 mg/kg in the final year on the Wilson's site ($p < 0.05$). Higher soil concentrations of Zn were required in wheat to increase grain values significantly above the control, with application rates greater than 161 mg Zn/kg in year one, 189 mg Zn/kg in year two and 242 mg Zn/kg in year three.

The differences in early plant growth and grain yield response data due to metal availability between the two soil types is attributed to soil properties including differences in soil pH and soil organic matter content (Whatmuff et al. 2004; McLaughlin et al. 2003). These parameters are being investigated further by Warne et al. (2007) for soils from the NBRP sites in order to determine which soil properties control the toxicity and bioavailability of Cu and Zn.

Table 15. The effect of increasing total soil Zn concentrations (mg/kg) on Zn concentrations in harvested grain (mg/kg) for the Brennan and Wilson's sites over three years for three consecutive crops.

Site		Brennan's		
Year		2003	2004	2005
Zinc treatment	Crop	Wheat	Canola	Wheat
	Rate Zn (mg/kg)	Zn conc. In grain (mg/kg)	Zn conc. In grain (mg/kg)	Zn conc. In grain (mg/kg)
0	0	22.0	24.5	16.5
1	14	31.5	35.0	25.5
2	21	35.0	38.5*	40.0
3	32	45.5	39.0*	35.5
4	48	46.5	47.0*	43.0
5	72	46.0	48.5*	38.0
6	108	56.0	51.0*	47.0
7	161	62.5*	55.0*	45.0
8	242	77.0*	94.5*	66.5*
9	363	86.5*	85.5*	71.5*
10	726	134.5*		114*
11	1452			
Mean		58.5	51.9	49.3
Lsd (p=0.05)		36.4	13.4	33.4
Site		Wilson's		
Year		2003	2004	2005
Zinc treatment	Crop	Canola	Wheat	Canola
	Rate Zn (mg/kg)	Zn conc. In grain (mg/kg)	Zn conc. In grain (mg/kg)	Zn conc. In grain (mg/kg)
0	0	45.5	18.5	36.5
1	25	60.0	17.5	41.0
2	37	68.0	20.5	48.5
3	56	70.5*	13.0	54.0
4	84	89.0*	11.5	50.0
5	126	99.0*	43.5	78.0*
6	189	105.0*	62.0*	64.5*
7	283	121.3*	58.5*	75.1*
8	425	118.7*	36.5	
9	637		18.5	
10	1274		19.0	
11	2548		48.5	
Mean		86.3	30.6	55.9
Lsd (p=0.05)		22.5	31.1	21.04

Included also are the l.s.d. values for each growth parameter following analysis of variance at p=0.05. Treatments with * are significantly different from the control. NLBAR = nitrogen limiting biosolids application rate. No values indicate that plants had reached the toxic threshold.

Given the acidic nature of the Western Australian sites, it would be expected that metal bioavailability would be increased compared with more neutral-alkaline sites examined by the NBRP in other states of Australia. In addition, the bioavailability of metal-salts would be expected to be more available compared with biosolid metals. A summary of the approximate Cu and Zn EC₅₀ values for two plant growth parameters is given in Table 16 and is compared with the Maximum Allowable Soil Contaminant Concentrations for biosolids amended soils used for food production (DEP, WRC & DOH 2002). It is difficult to compare the LC50 values between each site due to the different sensitivities of the crop species used.

Table 16. Approximate² Cu and Zn EC50 values for 8 week shoot dry matter and grain yield measured for wheat on the Brennan's site and canola on the Wilson's site). For comparison, soil metal limits for Cu and Zn are also included.

Site and crop				
	Wheat on Brennan's paddock 2003		Canola on Wilson's paddock 2003	
	Cu (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
	EC ₅₀	EC ₅₀	EC ₅₀	EC ₅₀
8 week biomass	936	363	341	283
Grain yield	936	242	1022	126
	Canola on Brennan's paddock 2004		Wheat on Wilson's paddock 2004	
	Cu (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
	EC ₅₀	EC ₅₀	EC ₅₀	EC ₅₀
8 week biomass	936	363	101	189
Grain yield	>936	242	1022	189
	Wheat on Brennan's paddock 2005		Canola on Wilson's paddock 2005	
	Cu (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
	EC ₅₀	EC ₅₀	EC ₅₀	EC ₅₀
8 week biomass	2044	242	227	84
Grain yield	2044	726	151	56
MACC ¹	100	200	100	200

¹ MACC = Maximum Allowable Soil Contaminant Concentration for biosolids amended soils used for food production (DEP, WRC & DOH 2002).

² Values selected are the closest rate corresponding to a 50% reduction and need to be calculated accurately.

The metal concentrations given are the target rates applied and not the actual measured amounts.

Effects of metals on soil microbial function and earthworms

A summary of Substrate-Induced Nitrification (SIN), Substrate-Induced Respiration (SIR) and Sub-lethal and lethal effects of metals on earthworms was presented in the July 2005 progress report. Earthworm toxicity values specific to the WA soils are summarised in Table 17.

Table 17. Toxicity values and 95% fiducial limits in brackets, for *Eisenia andrei* exposed to copper and zinc for varying exposure periods in four sites. These are based on measured total concentrations (Whatmuff et al. 2004).

Site	Metal	EC20 (growth)	LC50 values (mg/kg)			
		(mg/kg)				
		21 day	7 day	14 day	21 day	
Night paddock [#] (NSW)	Cu	310 (57-1684)	836 (822-850)	654 (610-700)	625 (578-677)	
	Zn	1255 (888-1775)	1490 (1370-1625)	1410 (1342-1480)	1380 (1242-1525)	
Flat paddock [#] (NSW)	Cu	143 (0.9-22000)	258 (244-271)	187 (185-190)	179 (174-184)	
	Zn	358 (168-764)	530 (519-542)	472 (463-481)	473 (460-487)	
Wilson's* (WA)	Cu	1691 NC	4900** (627-38320)	495 (262-933)	495 (179-1364)	
	Zn	563 (7.6-41500)	863 (592-1259)	831 (487-1420)	832 (473-1462)	
Dutson Downs [#] (Vic)	Cu	189 (87-411)	382 (317-461)	300 (233-388)	299 (226-397)	
	Zn	336 (124-906)	373 (367-380)	370 (359-382)	351 NC	

[#] EC50 values based on measured total concentrations

* EC20 and EC50 values based on nominal concentrations and hence tend to have large 95% confidence limits

** 50% mortality not reached, so the stated value is an extrapolation and has large Confidence Intervals

Source Whatmuff et al. (2004).

Biosolids experiment

Cadmium

Concentrations of Cd in the soil ranged from 0.02 to 0.08 mg Cd/kg in the control treatments over the three years on the two sites to a maximum of 0.14 mg Cd/kg at the highest biosolids rate (4.5xNLBAR) (Table 18). There were no significant differences in concentrations of Cd between the 1xNLBAR, which is typically used for biosolids applications in Western Australia, and the standard inorganic fertiliser treatment over all sampling times ($p < 0.05$). There were no significant differences in soil Cd concentrations between the Beenyup and Woodman Point biosolids at any treatment and therefore combined mean values are given.

Table 18. Combined mean soil Cd concentrations (mg/kg) in the surface 0-10 cm of Beenyup and Woodman Point biosolids to the Brennan's and Wilson's paddock sites from 2003 to 2005.

	Brennan's Cd (mg/kg)			
Treatment	T0	T1	T2	T3
Control (nil.)	0.02	0.03	0.03	0.03
0.5xNLBAR	0.03	0.04	0.04	0.06
1.0xNLBAR	0.03	0.04	0.04	0.05
1.5xNLBAR	0.05	0.05	0.04	0.05
3xNLBAR	0.07*	0.03	0.06*	0.07
4.5xNLBAR	0.09*	0.04	0.07*	0.07
1.5xNLBAR repeat	0.05	0.03	0.06*	0.08
Inorganic Fertiliser	0.02	0.04	0.03	0.05
I.s.d ($p=0.05$)	0.042	ns	0.012	ns
	Wilson's Cd (mg/kg)			
Treatment	T0	T1	T2	T3
Control (nil.)	0.02	0.07	0.08	0.08
0.5xNLBAR	0.03	0.08	0.08	0.10
1.0xNLBAR	0.03	0.09*	0.09	0.10
1.5xNLBAR	0.05	0.08	0.10	0.10
3xNLBAR	0.07*	0.08	0.09	0.11*
4.5xNLBAR	0.09*	0.12*	0.14*	0.13*
1.5xNLBAR repeat	0.05	0.08	0.10	0.12*
Inorganic Fertiliser	0.02	0.07	0.09	0.08
I.s.d ($p=0.05$)	0.042	0.016	0.029	0.026

MACC ¹	1 mg/kg				
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As no significant differences were obtained between the Beenyup and Woodman Point biosolids ($p < 0.05$), the mean value has been given for each site. Included also are the l.s.d. values for each growth parameter following analysis of variance at $p = 0.05$. Treatments with * are significantly different from the control. NLBAR = nitrogen limiting biosolids application rate.

¹ Maximum Allowable Soil Contaminant Concentration for agricultural lands from NSW EPA (1997), whereas Western Australian guidelines stipulate 3.0 mg Cd/kg (DEP, WRC & DOH 2002). T0=2003 post application, T1=2003 harvest, T2=2004 harvest, T3=2005 harvest.

Soil Cd concentrations at all biosolid rates were well below the Western Australian guidelines of 3.0 mg Cd/kg (DEP, WRC & DOH 2002) and NSW EPA Biosolids Guideline MACC of 1.0 mg Cd/kg on both soils at all sampling events. Data collected from the NBRP research suggest that Cd uptake by wheat plants is affected by a number of soil factors and thus Cd soil concentration values have been revised to take into account soil pH (soil acidity) and clay content (McLaughlin et al. 2006). The suggested values are presented in Table 19, and even on the acidic sandy soils used in this experiment for biosolids application, soil Cd concentrations that would result in wheat grain exceeding Australian Cd food standards was not reached.

Table 19. Suggested maximum permitted Cd concentrations in soils receiving biosolids to ensure wheat grain would not exceed Australian Cd food standards (from McLaughlin et al. 2006)

	Clay content (%)		
	5	25	50
pH	Mg Cd/kg soil		
4.5	0.3	0.9	1.6
5.5	0.6	1.1	1.8
6.5	0.9	1.4	2.1
7.5	1.1	1.6	2.3
8.5	1.4	1.9	2.6

McLaughlin et al. (2006)

Copper

Concentrations of Cu in the soil generally increased with increasing rates of biosolids application and were all significantly higher ($p < 0.05$) than the control at most rates of 3xNLBAR and at all rates of 4.5xNLBAR (Table 20). There were no significant differences between the 1xNLBAR, which is typically used for biosolids applications in Western Australia, and the standard inorganic fertiliser treatment. In general there were no differences between the two WWTP's, except at sampling time T2 on the Brennan's site, in which the Cu was higher in the Beenyup biosolids. The MACC for Cu of 100 mg/kg was not exceeded at any of the biosolids application rates.

Table 20. Concentrations of Cu (mg/kg) in the surface 0-10 cm following application of Beenyup and Woodman Point biosolids to the Brennan's and Wilson's paddock sites over four sampling times.

Brennan's					
Treatment	T0	T1	T2		T3
WWTP			Beenyup	Woodman	
Control (nil.)	5	3	3	4	3
0.5xNLBAR	7	4	4	4	5
1.0xNLBAR	12	5	5	5	8
1.5xNLBAR	21	13*	6	8	10
3xNLBAR	25*	7	19*	10*	24*
4.5xNLBAR	38*	10*	29*	19*	27*
1.5xNLBAR repeat	18	5	15*	16*	31*
Inorganic Fertiliser	5	6	3	3	3
I.s.d (p=0.05)	17.9	6.0	4.5	4.5	11.0
Wilson's					
Treatment	T0	T1	T2	T3	
Control (nil.)	5	3	4	4	
0.5xNLBAR	13	7	6	10	
1.0xNLBAR	25	9*	10	11	
1.5xNLBAR	20	8	17*	16*	
3xNLBAR	38*	12*	21*	24*	
4.5xNLBAR	72*	33*	44*	44*	
1.5xNLBAR repeat	18	9*	24*	32*	
Inorganic Fertiliser	5	4	5	4	
I.s.d (p=0.05)	24.5	5.4	11.5	9	
MACC ¹ 100 mg Cu/kg					

Where no significant differences were obtained between the Beenyup and Woodman Point biosolids ($p < 0.05$), the mean value has been given for each site, otherwise both WWTPs are given. Included also are the I.s.d. values for each growth parameter following analysis of variance at $p = 0.05$. Treatments with * are significantly different from the control. NLBAR = nitrogen limiting biosolids application rate. ¹ Maximum Allowable Soil Contaminant Concentration for agricultural lands from DEP, WRC & DOH (2002). T0=2003 post application, T1=2003 harvest, T2=2004 harvest, T3=2005 harvest.

Zinc

Concentrations of Zn in the soil generally increased with increasing rates of biosolids application and were all significantly higher ($p < 0.05$) than the control at 4.5xNLBAR over the three years of the experiment (Table 21). There were no significant differences between the 1xNLBAR, which is typically used for biosolids applications in Western Australia, and the standard inorganic fertiliser treatment. In general there were no differences between the two WWTP's, except at sampling time T2 on the Brennans site at 4.5xNLBAR, in which the Zn was higher in the Beenyup biosolids and on the Wilson's site at T3 at 4.5xNLBAR, whereby the Zn was higher in the Woodman Point biosolids. The MACC for Zn of 200 mg/kg was not exceeded at any of the biosolids application rates.

Table 21. Concentrations of Zinc (mg/kg) in the surface 0-10 cm following application of Beenyup and Woodman Point biosolids to the Brennan's and Wilson's paddock sites over four sampling times.

Brennan's Zn (mg/kg)					
Treatment	T0	T1	T2		T3
WWTP			Beenyup	Woodman	
Control (nil.)	6	9	9	9	9
0.5xNLBAR	6	9	9	9	9
1.0xNLBAR	8	9	9	9	9
1.5xNLBAR	12	13*	9	9	9
3xNLBAR	15	9	12*	9	15
4.5xNLBAR	31*	12*	17*	11	16*
1.5xNLBAR repeat	11	9	11	10	20*
Inorganic Fertiliser	6	10	9	9	9
<i>l.s.d (p=0.05)</i>	14.9	2.8	2.3	2.3	6.2
Wilson's Zn (mg/kg)					
Treatment	T0	T1	T2	T3	
WWTP				Beenyup	Woodman
Control (nil.)	6	9	9	9	9
0.5xNLBAR	10	9	9	10	9
1.0xNLBAR	16	9	10	10	10
1.5xNLBAR	13	9	14	9	13
3xNLBAR	22*	10	15	13	16*
4.5xNLBAR	42*	20*	29*	21*	26*
1.5xNLBAR repeat	12	10	18*	16*	25*
Inorganic Fertiliser	6	9	9	9	10

<i>I.s.d</i> ($p=0.05$)	14	2.8	7.4	4.9	4.9
MACC ¹	200 mg/kg				

Where no significant differences were obtained between the Beenyup and Woodman Point biosolids ($p<0.05$), the mean value has been given for each site, otherwise both WWTPs are given. Included also are the *I.s.d.* values for each growth parameter following analysis of variance at $p=0.05$. Treatments with * are significantly different from the control. NLBAR = nitrogen limiting biosolids application rate. ¹ Maximum Allowable Soil Contaminant Concentration for Grade C1 agricultural lands (DEP, WRC & DOH 2002). T0=2003 post application, T1=2003 harvest, T2=2004 harvest, T3=2005 harvest.

Other soil elements

Immediately after application (T₀), biosolids increased soil levels of Ca, Mg, Mn, Ni and S in the 4.5xNLBAR treatment on both the Brennan's and Wilson's paddock sites ($p<0.05$). By the end of the first season (T₁), soil concentrations of Mg and S were still elevated in the 4.5X NLBAR on both sites and Ca on the Brennan's site, although only at the lower rates. By the end of the second season (T₂), concentrations of S, Mn, Mg and Ca were higher in the highest rates of biosolids (typically the 4.5xNLBAR), with the trend being for these elements to be higher where Beenyup biosolids had been applied ($p<0.05$). By the end of the final season (T₃), similar trends were noted to previous seasons, with concentrations of Ca, S and Mn still elevated at the highest biosolids application rates (typically 3xNLBAR and 4.5xNLBAR), but also appearing in the 1.5xNLBAR repeat application. To be noted again was the higher concentrations of soil Mn in the Beenyup biosolids treatments. The only unusual spike in metal concentrations was for Ni on the Brennan's site, which was marginally higher in the 4.5xNLBAR and 1.5xNLBAR repeat application (1.5xNLBAR). There were no changes measured in concentrations of soil Al, Fe, Cr or Pb at any biosolids treatment compared with the control treatment at any of the sampling dates (data not presented).

Soil carbon, nitrogen and phosphorus

Soil carbon

Concentrations of soil organic C, N and available P were increased significantly as the rate of biosolids was increased above that of the control ($p < 0.05$). On both Western Australian sites, soil organic C increased by approximately 0.4% above that of the control at biosolid applications at 1xNLBAR ($p < 0.05$) and continued to increase proportionally with increasing rates (Table 22). These rate increases would be expected given that Perth biosolids contain approximately 40% total C on a dry weight basis.

Table 22. Combined mean soil total C concentrations (mg/kg) in the 0-10 cm surface immediately following application (T_0), and following harvest in 2003, 2004 and 2005 for the biosolids experiment on the Brennan's and Wilson's paddock sites

Treatment	Total carbon (mg/kg)							
	T_0	Brennans			Wilson's			
		2003	2004	2005	T_0	2003	2004	2005
Control (nil.)	6000	6450	6350	6550	13600	13917	14667	15167
0.5xNLBAR	7817	7783	7967	7917	16500	17283	17700	19150*
1.0xNLBAR	9733*	7200	8117	9167	19517*	18667*	19533*	20200*
1.5xNLBAR	10967*	9400	8667	10350*	21850*	19267*	24167*	19017*
3xNLBAR	13600*	10800	10717*	14683*	25067*	23417*	23267*	20933*
4.5xNLBAR	15733*	14517*	11933*	15100*	34133*	26167*	32200*	24500*
1.5xNLBAR repeat	9817*	8900	11733*	16600*	20783*	20367*	23833*	24517*
Inorganic Fertiliser	6500	8317	7183	9067	14633	16600	17983	17700
I.s.d. ($p=0.05$)	3487.7	5671.8	2324.6	3718.4	3068.3	4058	4660.3	3846.3

As no significant differences were obtained between the Beenyup and Woodman Point biosolids ($p < 0.05$), for soil carbon, the mean value has been given for each site. Included also are the I.s.d. values for each growth parameter following analysis of variance at $p=0.05$. Treatments with * are significantly different from the control (nil). NLBAR = nitrogen limiting biosolids application rate. T_0 =2003 post application, T_1 =2003 harvest, T_2 =2004 harvest, T_3 =2005 harvest.

Soil nitrogen

Immediately after application (T₀), total soil N was increased significantly at 0.5xNLBAR on the Brennan's paddock site and at 1xNLBAR on the Wilson's paddock site above that of the control (nil fertiliser). The concentration of N at 1xNLBAR was significantly higher compared with the inorganic fertiliser treatment of 100 kg/ha di-ammonium phosphate (DAP). Soil N concentrations would be expected to increase in the fertiliser treatment later in the season following the application of 100 kg/ha urea as a post sowing N fertiliser. Total N measures the sum of organic N and inorganic N fractions in the soil. Organic N, however, must first be mineralised to inorganic N before plants can utilise it. Inorganic N in the form of nitrate in the soil is soluble and can be readily leached and contaminate groundwater if applied in excess of plant requirements.

Table 23. Combined mean soil total N (mg/kg) in the 0-10 cm surface immediately following application (T₀), and following harvest in 2003, 2004 and 2005 for the biosolids experiment on the Brennan's and Wilson's paddock sites

Treatment	Total nitrogen (mg/kg)							
	T ₀	Brennan's			Wilson's			
		2003	2004	2005	T ₀	2003	2004	2005
Control (nil.)	390	400	430	493	832	902	925	933
0.5xNLBAR	582*	530	548	602	1090	1168	1153	1208
1.0xNLBAR	827*	502	548	737	1508*	1260	1275	1298*
1.5xNLBAR	1017*	757	643*	852	1802*	1340*	1813*	1315*
3xNLBAR	1427*	975	865*	1462*	2398*	1912*	1663*	1577*
4.5xNLBAR	1763*	1450*	1002*	1503*	3598*	2403*	2705*	1922*
1.5xNLBAR repeat	892*	905	982*	1697*	1703*	1380*	1807*	1950*
Inorganic Fertiliser	413	500	475	553	903	1063	1158	1117
I.s.d. (p=0.05)	405.2	650.0	202.4	385.3	347.7	386.4	429.4	299.4

As no significant differences were obtained between the Beenyup and Woodman Point biosolids ($p < 0.05$), for any nutrient, the mean value has been given for each site. Included also are the I.s.d. values for each growth parameter following analysis of variance at $p = 0.05$. Treatments with * are significantly different from the control (nil). NLBAR = nitrogen limiting biosolids application rate. T₀=2003 post application, T₁=2003 harvest, T₂=2004 harvest, T₃=2005 harvest.

Soil phosphorus

Total P gives an indication of the total P loadings in the soil and is used for calculating nutrient budgets and potential leaching. Increasing application rates of biosolids increased the concentrations of total P on the Brennan's paddock site from 69 mg P/kg in the control to 747 mg P/kg at the 4.5xNLBAR and on the Wilson's site from 212 mg P/kg in the control to 1,240 mg P/kg at 4.5xNLBAR immediately after application. These increases are consistent with expected loading values. No significant differences were obtained between the Beenyup and Woodman Point biosolids ($p>0.05$), in the majority of sampling events and so the mean value has been given for each site. The exceptions were as follows: 2003 on the Wilson's site where mean total P in Beenyup treatments (344 mg P/kg) was higher than for Woodman Point treatments (296 mg P/kg). 2004 on the Wilson site where mean total P in Beenyup biosolids (432 mg P/kg) was higher than for Woodman Point treatments (335 mg P/kg). 2004 on the Brennan's site site where mean total P in Beenyup treatments (219 mg P/kg) was higher than for Woodman Point treatments (149 mg P/kg). ($p<0.05$). Beenyup biosolids contains a higher concentration of P than Woodman Point biosolids.

Table 24. Combined mean soil total P (mg/kg) in the 0-10 cm surface immediately following application (T_0) and following harvest in 2003, 2004 and 2005 for the biosolids experiment on the Brennan's and Wilson's paddock sites.

Treatment	Total phosphorus (mg/kg)							
	Brennan's				Wilson's			
	T_0	2003	2004	2005	T_0	2003	2004	2005
Control (nil.)	69	82	87	82	212	206	188	202
0.5xNLBAR	133	109	104	116	505	273	238	303
1.0xNLBAR	215	109	135	162	545	304*	307	322
1.5xNLBAR	392*	218*	145	166	461	259	360	347
3xNLBAR	372*	154*	247*	289*	751*	353*	455*	452*
4.5xNLBAR	747*	194*	348*	334*	1240*	653*	786*	679*
1.5xNLBAR repeat	321	121	294*	455*	436	302*	497*	655*
Inorganic Fertiliser	103	108	87	132	234	208	237	363
I.s.d. ($p=0.05$)	336.2	65.5	60.1	118.3	437.5	79.6	191.4	165.0

No significant differences were obtained between the Beenyup and Woodman Point biosolids ($p>0.05$), in the majority of sampling events and so the mean value has been given for each site. The exception being that Beenyup resulted in higher levels of total P than Woodman Point in 2003 and 2004 on the Wilson's site and 2004 on the Brennan's site ($p<0.05$). Included also are the I.s.d. values for each growth parameter following analysis of variance at $p=0.05$. Treatments with * are significantly different from the control (nil). NLBAR = nitrogen limiting biosolids application rate. T_0 =2003 post application, T_1 =2003 harvest, T_2 =2004 harvest, T_3 =2005 harvest.

Soil available phosphorus

Soil available P measured as Colwell bicarbonate extractable P gives an indication of the amount of P that is readily plant available. Soils with a high phosphorus retention index (PRI), such as those high in Fe and Al reduce concentrations of plant available P. There were no differences between soil available P concentrations between the fertiliser control and the 1xNLBAR at both sites immediately after application (Table 25, $p>0.05$). The concentrations of available P were elevated at 3xNLBAR and 4.5xNLBAR treatments. The exceptions were as follows: 2003 on the Wilson's site where mean available P in Beenyup treatments (108 mg P/kg) was higher than for Woodman Point treatments (70 mg P/kg); 2004 on the Wilson site where mean available P in Beenyup biosolids (109 mg P/kg) was higher than for Woodman Point treatments (92 mg P/kg); 2004 on the Brennan's site where mean available P in Beenyup treatments (73.5 mg P/kg) was higher than for Woodman Point treatments (52.3 mg P/kg) ($p<0.05$).

Table 25. Combined mean soil available P (mg/kg) in the 0-10 cm surface immediately following application (T_0) and following harvest in 2003, 2004 and 2005 for the biosolids experiment on the Brennan's and Wilson's paddock sites

Treatment	Soil available phosphorus (mg/kg)							
	Brennan's				Wilson's			
	T_0	2003	2004	2005	T_0	2003	2004	2005
Control (nil.)	24.7	12.0	18.2	18.5	29.5	26.5	29.7	28.2
0.5xNLBAR	29.5	31.0	25.5	27.0	50.2	46.0	47.7	47.5
1.0xNLBAR	64.5	25.0	34.7	47.2	64.7	67.7	69.3*	64.8*
1.5xNLBAR	50.5	85.0*	45.5	55.5	114.8	73.2	82.5*	84.7*
3xNLBAR	92.3*	127.0*	89.5*	89.7*	210*	154.8	133.3*	122.3*
4.5xNLBAR	189.8*	155.0*	136.9*	126.7*	315*	250.0	228.3*	203.3*
1.5xNLBAR repeat	71.2	61.0	125.0*	176.7*	99.3	65.3	166.7*	213.3*
Inorganic Fertiliser	34.0	27.0	27.9	27.8	38	31.5	48.5	53.2
I.s.d. ($p=0.05$)	39.9	82.8	30.6	39.2	72.8	43.0	26.3	31.62

No significant differences were obtained between the Beenyup and Woodman Point biosolids ($p>0.05$), in the majority of sampling events and so the mean value has been given for each site. The exception being that Beenyup resulted in higher levels of available P than Woodman Point in 2003 and 2004 on the Wilson's site and 2004 on the Brennan's site ($p<0.05$). Included also are the I.s.d. values for each growth parameter following analysis of variance at $p=0.05$. Treatments with * are significantly different from the control (nil). NLBAR = nitrogen limiting biosolids application rate. Soil available phosphorus as per Colwell. T_0 =2003 post application, T_1 =2003 harvest, T_2 =2004 harvest, T_3 =2005 harvest.

Soil pH

Results for changes in surface (0 – 10 cm depth) soil pH (pH measured in 0.01 M CaCl₂, four hour extraction, 1:5 soil solution extract (NSW)) are presented in Table 26. Soil pH gives an indication of the acidity or alkalinity of the soil. On the Brennan's site, increasing the rate of biosolids tended to decrease soil pH, being significantly lower than the control at the highest rate ($p < 0.05$). At the 1.0xNLBAR however, there was no decrease in soil pH. On the Wilson's site, the addition of biosolids generally increased soil pH so that the highest rate of biosolids was higher than the control ($p < 0.05$). At the 1.0xNLBAR, pH was higher than the control. There was often a difference between the two biosolids products as the addition of Beenyup biosolids generally resulted in higher soil pH than equivalent rates of Woodman Point biosolids ($p < 0.05$). The difference was usually in the order of 0.1 units.

Table 26. Combined mean soil pH in the 0-10 cm surface immediately following application (T₀) and following harvest in 2003, 2004 and 2005 for the biosolids experiment on the Brennan's and Wilson's paddock sites

Treatment	Soil pH							
	T ₀	Brennan's			Wilson's			
		2003	2004	2005	T ₀	2003	2004	2005
Control (nil.)	6.2	5.9	5.8	6.0	5.3	4.4	4.5	
0.5xNLBAR	6.1	5.7	5.8	5.7	5.4	4.6*	4.7*	
1.0xNLBAR	6.3	5.7	6.0	5.7	5.4	4.6*	4.8*	
1.5xNLBAR	6.3	5.7	5.8	5.7	5.1	4.6*	4.7*	
3xNLBAR	6.1	5.7	5.8	5.7	5.0	4.6*	4.7*	
4.5xNLBAR	6.0	5.5*	5.5	5.5*	4.7*	4.8*	5.0*	
1.5xNLBAR repeat	6.2	5.7	5.8	5.7	4.9*	4.6*	4.7*	
Inorganic Fertiliser	6.2	5.7	5.8	5.8	4.9*	4.5	4.5	
I.s.d. (p=0.05)	ns	0.33	ns	0.33	0.33	0.12	0.12	No data

The pH in Beenyup biosolids was generally about 0.1 units higher than in Woodman Point biosolids at any biosolids treatment on both sites ($p < 0.05$). Included also are the I.s.d. values for pH following analysis of variance at $p = 0.05$. Treatments with * are significantly different from the control (nil). NLBAR = nitrogen limiting biosolids application rate. T₀=2003 post application, T₁=2003 harvest, T₂=2004 harvest, T₃=2005 harvest.

Electrical Conductivity

The electrical conductivity of a soil sample gives an indication of the level of soil salinity. Soil salinity is considered almost negligible between 0-200 mS/m (i.e. 0-2.00 dS/m) (Moore, 1998). The Brennan's and the Wilson's site were non-saline at the commencement of the experiment and the addition of biosolids at 1xNLBAR did not increase soil salinity to levels greater than 200 mS/m (Table 27). The addition of biosolids, however, did increase the EC of the soil ($p < 0.05$).

Table 27. Combined mean soil electrical conductivity (EC) in the 0-10 cm surface immediately following application (T_0) and following harvest in 2003, 2004 and 2005 for the biosolids experiment on the Brennan's and Wilson's paddock sites

Treatment	Soil EC (1:5) dS/m							
	T_0	Brennan's			Wilson's			
		2003	2004	2005	T_0	2003	2004	2005
Control (nil.)		0.058	0.040	0.028		0.053	0.030	0.033
0.5xNLBAR		0.072	0.050	0.040*		0.079	0.038	0.042
1.0xNLBAR		0.070	0.060	0.038*		0.087*	0.047	0.047
1.5xNLBAR		0.097*	0.050	0.042*		0.092*	0.063	0.047
3xNLBAR		0.124*	0.070	0.043*		0.123*	0.078	0.058
4.5xNLBAR		0.137*	0.090	0.045*		0.201*	0.167*	0.087
1.5xNLBAR repeat		0.087*	0.110*	0.075*		0.097*	0.14*	0.132*
Inorganic Fertiliser		0.065	0.040	0.035		0.059	0.030	0.033
I.s.d. ($p=0.05$)		0.022	0.060	0.0078		0.031	0.076	0.0617

As no significant differences were obtained between the Beenyup and Woodman Point biosolids ($p < 0.05$), except on both sites in 2004 and on the Wilson's site in 2005, the mean value has been given for each site. Included also are the I.s.d. values for each growth parameter following analysis of variance at $p=0.05$. Treatments with * are significantly different from the control (nil). NLBAR = nitrogen limiting biosolids application rate. T_0 =2003 post application, T_1 =2003 harvest, T_2 =2004 harvest, T_3 =2005 harvest.

Effects of biosolids on soil microbial functions

Soil microbes showed no toxicity responses to biosolids as measured using SIR, even at high application rates. In its present form, the SIN test could not evaluate any beneficial effects of the added biosolids as it is limited by the addition of the NH_4 substrate and no inferences could be made about any nutrients added with the biosolids (Whatmuff et al. 2004)

Plant growth and grain yield

Year one (2003)

As with the metal-salt trials discussed previously, early growth measurements were made on wheat and canola crops established on the biosolids treatments as well as grain yield at harvest. Table 15 gives the mean shoot dry matter (g/20 plants) at eight weeks and harvest grain yields (t/ha) for the combined biosolids treatments on the Brennan and Wilson paddock sites. The data from Table 15 are also presented in graphical form in Figure 1 (grain yield) for both paddocks.

Increasing applications of biosolids did not affect plant germination or density in wheat on the Brennan's site, however canola germination on the Wilson's site was decreased at the 3xNLBAR and the 4.5xNLBAR, likely due to the heavy stubble load interfering with soil contact of the small seeds. Shoot dry matter of wheat and canola at 8 weeks and dry matter at harvest generally increased with increasing rates of biosolids to reach a maximum at 4.5xNLBAR. The final grain yield was highest at 3xNLBAR with 3.53 t/ha of wheat and 2.64 t/ha of canola recorded. A reduction in seed size at 4.5xNLBAR indicated moisture stress due to plant competition at this application rate. There were no differences in wheat grain yield between the inorganic fertiliser control and the 1xNLBAR measuring 2.72 t/ha and 2.42 t/ha, respectively ($p>0.05$). Canola grain yield, however, was higher at 1xNLBAR compared with the inorganic fertiliser treatment, measuring 2.08 t/ha and 1.52 t/ha, respectively ($p<0.05$).

Year two (2004)

Mean grain yields in the DAP + urea inorganic fertiliser control were similar between both the 2003 and 2004 season for each crop type, regardless of the site. The mean grain yield of wheat in 2003 measured 2.72 t/ha and in 2004 measured 2.73 t/ha. Grain yield of canola in 2003 measured 1.52 t/ha and in 2004 measured 1.45 t/ha and therefore these values can be compared relative to the biosolids treatments.

The residual value of biosolids in the second year after application could be measured in increasing eight week shoot dry matter, dry matter at harvest and final grain yield for both canola and wheat above that of the nil control (Table 16). The residual applications of biosolids at $>1.5xNLBAR$ were higher than the freshly applied fertiliser, although there were no differences between the 1xNLBAR and the freshly applied inorganic fertiliser treatment. Grain yield of canola on the Brennan's paddock site was greatest in the 1.5xNLBAR repeat application (i.e. total of 3xNLBAR) and was significantly higher than the original 3xNLBAR application measuring 2.76 t/ha and 1.82 t/ha, respectively ($P<0.05$). There were no differences in grain yield of wheat on the Wilson's paddock site between the 1.5xNLBAR repeat application and the 3xNLBAR ($p>0.05$).

Year three (2005)

Wheat growth on the Brennan's site following three successive years of nil fertiliser was poor, yielding 0.79 t/ha and canola on the Wilson's site yielded only 0.42 t/ha, indicating that plant nutrients had slowly been depleted following three years of continual cropping. As in previous years, there were no major differences between the two biosolids products, although in some treatments the residual Beenyup treatments yielded slightly better than the Woodman Point. After three seasons, wheat yield on the initial 1 x NLBAR treatment (1.82 t/ha) was no different to the annual fertiliser control (1.78 t/ha). Grain yield of canola, however, were higher in the inorganic fertiliser treatment (1.44 t/ha) than at 1xNLBAR

(1.07 t/ha), suggesting that residual nutrient levels had declined in the biosolids. Canola yields were higher ($p < 0.05$) in Beenyup biosolids at 0.5xNLBAR than Woodman Point biosolids.

Wheat growth on the Brennan's site following the repeat 1.5 x NLBAR treatment, for the third successive year (i.e. cumulative total of 4.5 x NLBAR) yielded an average of 3.8 t/ha, which was higher than the initial 4.5 x NLBAR of 2.81 t/ha (5%LSD = 0.77). In the canola, the repeat 1.5 x NLBAR treatment, for the third successive year (i.e. cumulative total of 4.5 x NLBAR) yielded an average of 2.4 t/ha, which was significantly higher than the initial 4.5 x NLBAR of 1.30 t/ha (5%LSD = 0.33). Wheat yields were higher in the repeat application of Woodman Point (1.5xNLBAR) than Beenyup. In addition, wheat yields were higher in Beenyup biosolids at 0.5xNLBAR, 1xNLBAR and 3.5xNLBAR. However, given that no discernable trend was apparent, the mean values have been given for each site.

Table 28. Mean plant density; shoot dry matter measured eight weeks after germination, final grain yields and dry matter for wheat on the Brennan's site and canola on the Wilson's site for the biosolids trial in year one.

Year one (2003)					
Wheat on the Brennan's paddock site					
Treatment	Plants/m ²	DM 20 plants (g)	Harvest dry wt (t/ha)	Harvest grain yield (t/ha)	100 seed wt (g)
Control (nil.)	95	9.9	3.0	1.26	3.79
0.5xNLBAR	90	18.8	6.1*	2.59*	4.04
1.0xNLBAR	94	25.2*	6.0*	2.42*	3.90
1.5xNLBAR	86	31.9*	8.1*	3.28*	3.65
3xNLBAR	77	48.3*	9.0*	3.52*	3.49
4.5xNLBAR	77	57.2*	9.2*	3.29*	3.10
1.5xNLBAR repeat	84	31.9*	7.2*	2.90*	3.90
Inorganic Fertiliser	104	20.5*	6.5*	2.72*	4.05
<i>Mean</i>	88	30.46	6.87	2.75	3.74
I.s.d. (p=0.05)	ns	7.38	1.33	0.679	0.346

Canola on the Wilson's paddock site					
Treatment	Plants/m ²	DM 20 plants (g)	Harvest dry wt (t/ha)	Harvest grain yield (t/ha)	100 seed wt (g)
Control (nil.)	116.7	7.52	2.1	0.93	0.37
0.5xNLBAR	106.5	20.09*	3.7*	1.71*	0.38
1.0xNLBAR	80.2	25.95*	4.6*	2.08*	0.38
1.5xNLBAR	86.4	32.37*	5.2*	2.43*	0.40
3xNLBAR	71*	41.57*	6.7*	2.64*	0.36
4.5xNLBAR	75*	45.57*	7.2*	2.32*	0.34*
1.5xNLBAR repeat	72.8*	31.96*	5.2*	2.28*	0.37
Inorganic Fertiliser	122.5	18.22*	3.5*	1.52*	0.38
<i>Mean</i>	91.39	27.91	4.79	1.99	0.37
I.s.d. (p=0.05)	34.72	5.28	1.13	0.48	0.03

As no significant differences were obtained between the Beenyup and Woodman Point biosolids (p=0.05), for any parameter, the mean value has been given for each site. Included also are the I.s.d. values for each growth parameter following analysis of variance at p=0.05. Treatments with * are significantly different from the control (nil). Ns=not significant. NLBAR = nitrogen limiting biosolids application rate.

Table 29. Mean plant density, shoot dry matter measured eight weeks after germination, final grain yields and dry matter for wheat on the Brennan's site and canola on the Wilson's site for the biosolids trial in Year two (2004).

Year two (2004)					
Canola on the Brennan's paddock site					
Treatment	Plants/m ²	DM 20 plants (g)	Harvest dry wt (t/ha)	Harvest grain yield (t/ha)	100 seed wt (g)
Control (nil.)	69.8	5.4	0.87	0.35	0.32
0.5xNLBAR	79	8.0	1.39	0.68	0.31
1.0xNLBAR	85.8	9.8	2.79*	1.25*	0.37
1.5xNLBAR	73.2	15.9*	2.10	1.23*	0.33
3xNLBAR	77.2	25.4*	3.60*	1.82*	0.37
4.5xNLBAR	79.3	37.5*	4.85*	2.42*	0.34
1.5xNLBAR repeat	64.8	48.7*	5.15*	2.76*	0.33
Inorganic Fertiliser	75	14.9*	2.69*	1.45*	0.35
Mean	75.5	20.7	2.93	1.50	0.34
I.s.d. (p=0.05)	ns	7.27	1.34	0.72	ns
Wheat on the Wilson's paddock site					
Treatment	Plants/m ²	DM 20 plants (g)	Harvest dry wt (t/ha)	Harvest grain yield (t/ha)	100 seed wt (g)
Control (nil.)	180	2.0	1.99	2.04	3.75
0.5xNLBAR	199	6.2*	2.81	2.43	4.07
1.0xNLBAR	180	10.1*	4.37*	3.29*	3.89
1.5xNLBAR	184	12.2*	4.25*	3.60*	3.96
3xNLBAR	183	19.8*	4.56*	3.36*	3.41*
4.5xNLBAR	186	23.7*	5.83*	3.43*	2.92*
1.5xNLBAR repeat	184	27.0*	5.33*	3.10*	2.94*
Inorganic Fertiliser	169	6.6*	3.61*	2.73*	3.74
Mean	183	13.4	4.09	3.00	3.59
I.s.d. (p=0.05)	ns	1.87	1.00	0.62	0.22

As no significant differences were obtained between the Beenyup and Woodman Point biosolids ($p < 0.05$), for any parameter, the mean value has been given for each site.

Included also are the I.s.d. values for each growth parameter following analysis of variance at $p = 0.05$. Treatments with * are significantly different from the control (nil). Ns=not significant. NLBAR = nitrogen limiting biosolids application rate.

Table 30. Mean plant density, shoot dry matter measured eight weeks after germination, final grain yields and dry matter for wheat on the Brennan's site and canola on the Wilson's site for the biosolids trial in Year three (2005).

Year three (2005)						
Wheat on the Brennan's paddock site						
Treatment	Plants/m ²	DM 20 plants (g)	Harvest dry wt (t/ha)	Harvest grain yield (t/ha)	100 seed wt (g)	
Control (nil.)	85.1	2.2	0.52	0.78	4.22	
0.5xNLBAR	88.2	3.4	0.95	1.45	4.54	
1.0xNLBAR	82.9	4.1	1.26	1.82*	4.51	
1.5xNLBAR	75.8	5.1	0.79	1.49	4.48	
3xNLBAR	79.5	5.1	1.41*	1.96*	4.51	
4.5xNLBAR	82.3	8.9*	2.52*	2.81*	4.50	
1.5xNLBAR repeat	76.2	24.9*	3.28*	3.78*	4.10	
Inorganic Fertiliser	74.9	8.4*	1.30	1.77*	4.56	
Mean	80.6	7.8	1.50	1.98	4.43	
I.s.d. (p=0.05)	ns	3.39	0.631	0.774	ns	
Canola on the Wilson's paddock site						
Treatment	Plants/m ²	DM 20 plants (g)	Harvest dry wt (t/ha)	Harvest grain yield (t/ha)	100 seed wt (g)	
Control (nil.)	71.2	1.7	1.23	0.42	0.40	
0.5xNLBAR	63.9	3.5	2.45*	0.85*	0.36*	
1.0xNLBAR	79.4	3.8*	2.98*	1.07*	0.39	
1.5xNLBAR	60.8	4.6*	3.30*	1.16*	0.38	
3xNLBAR	71.5	4.9*	3.03*	1.09*	0.40	
4.5xNLBAR	83.4	8.1*	3.86*	1.30*	0.39	
1.5xNLBAR repeat	73.9	17.5*	7.89*	2.35*	0.34*	
Inorganic Fertiliser	69.1	6.6*	4.45*	1.44*	0.36*	
Mean	71.7	6.5	3.65	1.210	0.38	
I.s.d. (p=0.05)	ns	1.88	1.055	0.327	0.028	

Canola yields were higher ($p < 0.05$) in Beenyup biosolids at 0.5xNLBAR than Woodman Point biosolids and wheat yields were higher in Beenyup biosolids at 0.5xNLBAR, 1xNLBAR and 3.5xNLBAR. Wheat yields were higher in the repeat application of Woodman Point (1.5xNLBAR) than Beenyup. Given no discernable trend, the mean values have been given for each site.

Included also are the I.s.d. values for each growth parameter following analysis of variance at $p = 0.05$. Treatments with * are significantly different from the control (nil). Ns=not significant.

NLBAR = nitrogen limiting biosolids application rate.

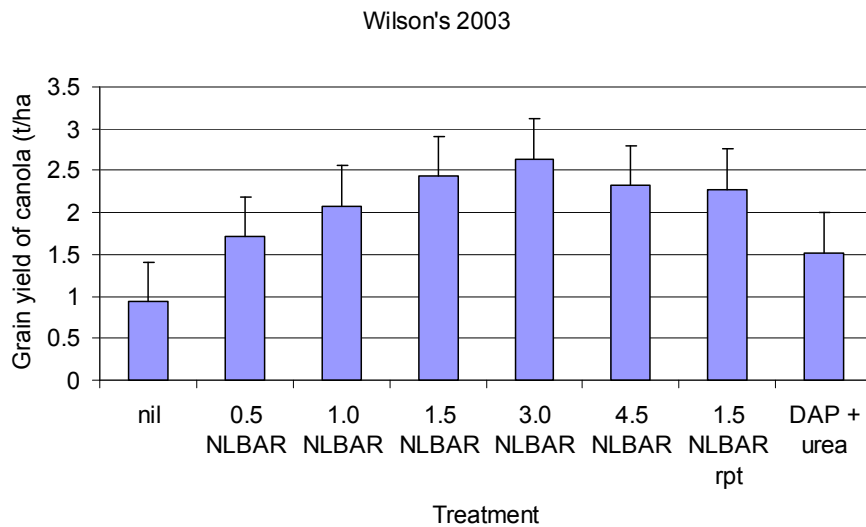
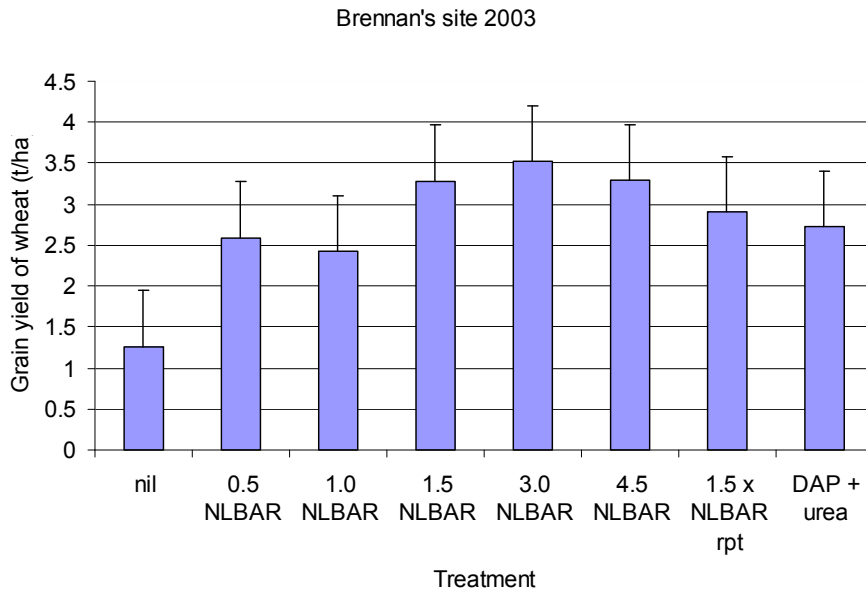


Figure 4. Relationship between grain yield of wheat and canola with fertiliser or increasing biosolids application following the 2003 (T1) harvest on two sites at Gillingarra, WA.

No significant differences obtained between the Beenyup and Woodman Point biosolids ($p < 0.05$) with mean values given for each site. The vertical bar represents the l.s.d. value ($p = 0.05$). NLBAR = nitrogen limiting biosolids application rate.

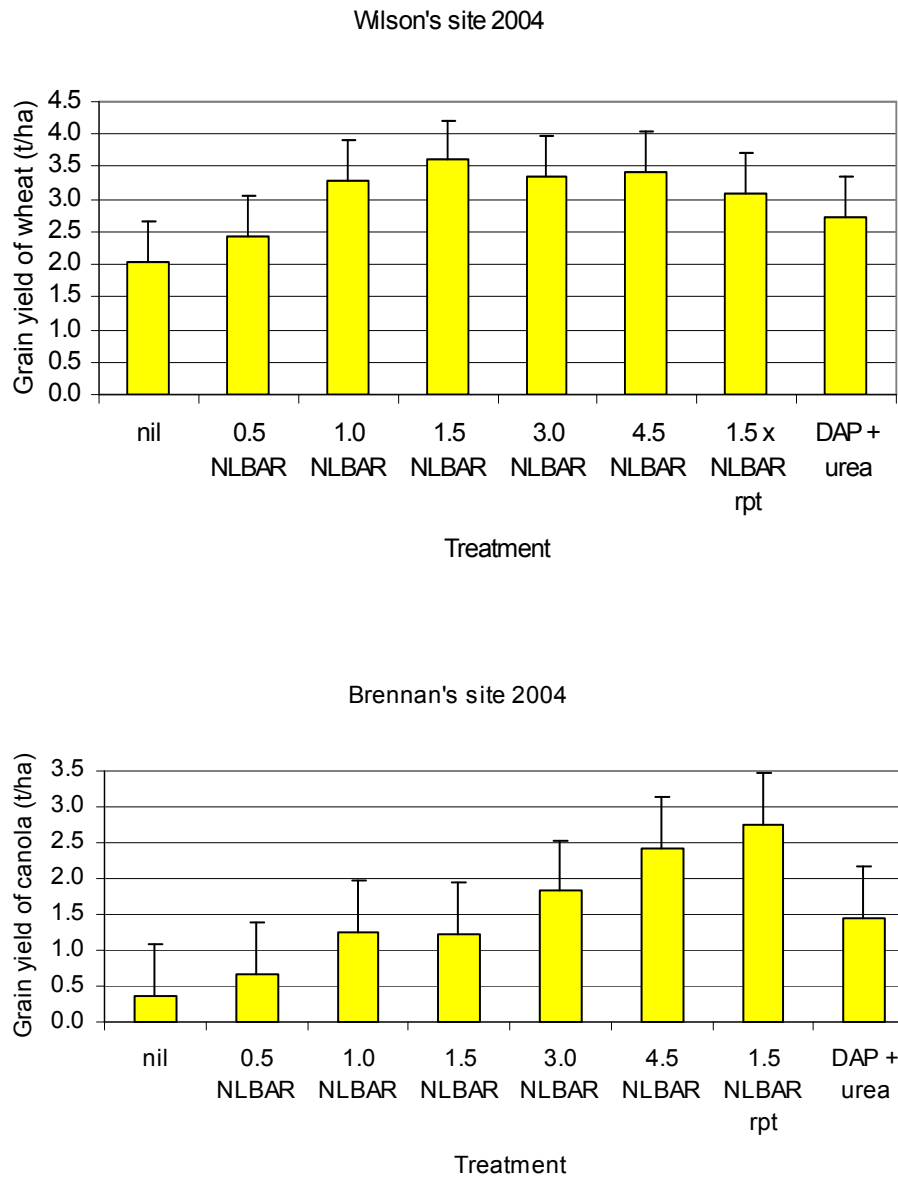


Figure 5. Relationship between grain yield of wheat and canola with fertiliser or increasing biosolids application following the 2004 (T2) harvest on two sites at Gillingarra, WA.

No significant differences obtained between the Beenyup and Woodman Point biosolids ($p < 0.05$) with mean values given for each site. The vertical bar represents the l.s.d. value ($p = 0.05$). NLBAR = nitrogen limiting biosolids application rate.

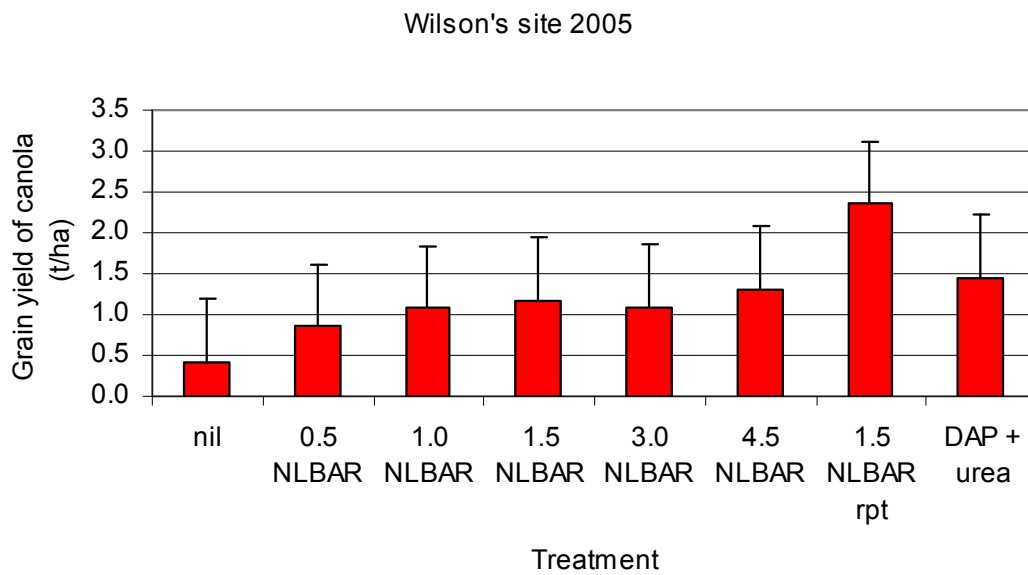
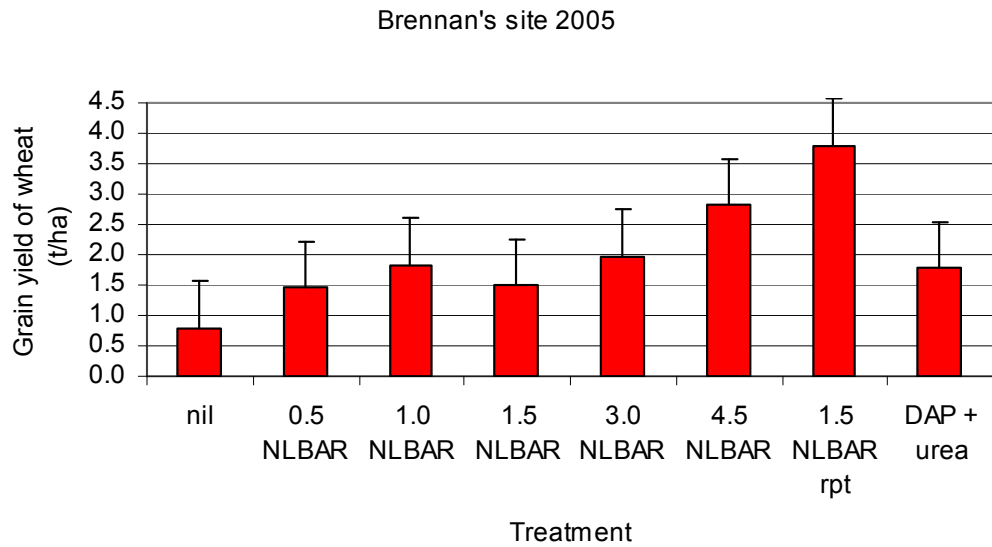


Figure 6. Relationship between grain yield of wheat and canola with fertiliser or increasing biosolids application following the 2005 (T3) harvest on two sites at Gillingarra, WA.

No significant differences obtained between the Beenyup and Woodman Point biosolids ($p < 0.05$) with mean values given for each site. The vertical bar represents the l.s.d. value ($p = 0.05$). NLBAR = nitrogen limiting biosolids application rate.

Comparison between metal-salts and biosolids experiments

According to Whatmuff et al. (2004), extreme soil metal concentrations such as those used in the salt trials represent cases of extreme contamination and are unlikely to occur outside an industry setting. However the phytotoxicity and food contamination responses are needed as endpoints for setting no-effect soil contamination limits, such as the application of biosolids to the same site regularly over a 100-year period. Soil metal levels will be examined further in the scope of the project to investigate long-term consequences of using biosolids.

Cadmium

Comparing the data for soil Cd in the metal-salt treated soils with those following biosolids application, it can be seen that the metal levels in the metal-salt treated soils are much higher than for the biosolids treatments. Concentrations of Cd in grain at the highest rate of biosolids were below those obtained in the metal-salts experiment (Table 10), and below the contaminant guidelines. The accumulation of cadmium in wheat grain from application of urban biosolids to soils in Australia was less than cadmium in a water-soluble form (McLaughlin et al 2006). Canola and wheat grain showed an increase in the concentration of Cd following the application of biosolids at 4.5xNLBAR above that of the control on both sites. Concentrations of Cd in wheat grain, increased from 0.017 mg Cd/kg in the nil fertiliser treatment to 0.033 mg Cd/kg at 4.5xNLBAR (2003-Brennan's) and in canola grain from 0.017 to 0.022 mg Cd/kg, respectively (2003-Wilson's).

Copper

Concentrations of soil Cu in the metal-salt treated soils were much higher than those following biosolids treatments as would be expected given the higher application rates. Warne et al. (2007 in press) showed that short-term (8 wk) biomass EC values were not related to harvest grain yield EC values. Field-based Cu toxicity was best modelled by pH measured in CaCl_2 and organic carbon content. There was little relationship between increasing concentrations of Cu in wheat grain to increasing rates of biosolids, although in canola grain a concentration of 4.35 mg Cu/kg was measured at 4.5xNLBAR at T1 as compared with the control of 2.73 mg Cu/kg.

Zinc

Concentrations of Zn in the metal-salt treated soils were much higher than those following biosolids treatments. Grain concentrations of Zn in canola increased from 33.3 to 49.8 mg Zn/kg as the rate of biosolids increased to 4.5xNLBAR at T1. In wheat grain, the increase was not as great ranging from 30.0 to 36.7 mg Zn/kg, respectively. Values for grain concentrations of Zn in canola of 99 mg Zn/kg and wheat of 77 mg Zn/kg were obtained in the metal-salt trial at the estimated LC50 value. Warne et al. (2007 in press) showed that short-term (8 wk) biomass EC values were not related to harvest grain yield EC values. Field-based Zn toxicity was best modeled using pH and the logarithm of cation exchange capacity.

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Appendices

Appendix 1

Summary of paper presented at the New Zealand Land Collective Treatment, Nelson March 2006

Biosolids: black gold in Western Australia

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ABSTRACT

Of the three major wastewater treatment plants in the capital city of Perth, Western Australia, two produce dewatered biosolids cake (DBC) and the third produces lime-amended biosolids (LAB). The total production of both DBC and LAB in the 2004/2005-year was approximately 20,000 tonnes dry solids (t DS) and is increasing at a growth rate of 4% yr⁻¹. The demand for Perth's biosolids as a low-grade fertiliser has outweighed supply and has achieved an average of 94% beneficial use for the past four years. The use of biosolids in Western Australia is strictly regulated by the '*Western Australian Guidelines for Direct Land Application of Biosolids and Biosolids Products 2002*' (DEP et al. 2002).

The three major users of biosolids in Western Australia include agriculture, forestry and composting accounting for 74%, 5% and 17% of the total biosolids production, respectively. Within the agricultural sector, the application of DBC commenced in 1996, mostly to wheat and canola crops in a dryland farming system. Local farmers have often referred to the biosolids as 'black gold' due to improvement in their crop yield and income following application. In forestry, biosolids research was commenced in 1998 on a 17 year-old pine plantation on the Swan Coastal Plain. Tree growth has improved significantly following the application of biosolids compared with inorganic fertiliser application, with no detrimental impact on groundwater quality. The composting of biosolids with other materials for domestic use and bagging has been practiced for more than 17 years.

This paper summarises the evolution and current use of biosolids in Western Australia and highlights the main research programs instigated by the Water Corporation to ensure that Perth's biosolids are used beneficially and safely in the environment. Research has concentrated mostly on plant and tree nutrient uptake, particularly nitrogen and phosphorus, heavy metals, composting of biosolids, flies and pathogens. Much of the research data has been collected within the Australian National Biosolids Research Project (NBRP).

KEYWORDS

Dewatered biosolids cake (DBC), lime-amended biosolids (LAB), agriculture, forestry, composting, flies

INTRODUCTION

In Perth during the early 1970s, sewage sludge produced by Wastewater Treatment Plants (WWTPs) was pumped into drying beds and then predominantly used by market gardens for growing vegetables. This practice continued until the late 1980s when associated health risks led to the construction of three incinerators to handle a large proportion of the sludge. By 1990 all three units were shut down due to high costs and odour issues. During this period, the sludge was also used in compost or land filled. A number of problems associated with the sludge drying beds, such as the lack of space, odours, flies and risks to groundwater contamination, resulted in them being progressively decommissioned. As a result, wastewater treatment plants were amplified or in some cases, newly constructed to process sludge.

The most recent wastewater treatments now use established processes that achieve significant pathogen reduction, such as anaerobic or aerobic digestion or thermal drying. Biosolids are defined as the stabilised organic solids produced by wastewater treatment processes, which in most cases can be beneficially recycled (NRMMC 2003). Perth's two major WWTPs, Woodman Point and Beenyup, stabilise their sludge by mesophilic anaerobic digestion. These secondary WWTPs are located along the coast and discharge effluent via outfalls to the ocean. Biosolids are rapidly dewatered by the use of enclosed centrifuges to approximately 20% total solids, and as such are a suitable consistency for transporting. The Subiaco WWTP stabilises raw sludge by the addition of lime, although previously it produced pelletised biosolids by thermal drying using an indirect rotary drum dryer, with pellets used for energy recovery at the plant (Bridle *et al.* 2000).

In total, these three WWTPs treated 280 ML/d of raw wastewater and produced 20,000 t DS of biosolids in 2004/2005, comprising 10,700 t DS DBC and 9,300 t DS LAB. All of the biosolids products meet minimum use criteria of Pathogen Grade P3 and Contaminant Grade C2 or better, as described in the Western Australian Guidelines (DEP *et al.* 2002), making them suitable for direct land application or reprocessing to improve quality. The Water Corporation has been monitoring biosolids quality (contaminant and pathogen) for a number of years with some parameters being reported at levels of less than detection. This has meant a less stringent monitoring program for the parameter listed in the guidelines, which then allows the Corporation to focus on other potential contaminants such as dioxins and alkyl-phenols.

The Water Corporation has achieved 100% beneficial use of DBC for the past four years. The demand for DBC currently out-weighs supply with indications from the current markets that they could handle supply well into the future. The three main outlets include direct land applications to agriculture and forestry plantations (79% of production) and production of an unrestricted product via composting (17% of production). The balance of production (5%) has been used in research. Current research relating to the constraints and beneficial use DBC will be discussed further in the scope of this paper.

RESEARCH PROGRAMS RELATING TO THE BENEFICIAL USE OF BIOSOLIDS

Agriculture

The agricultural region surrounding Perth consists of highly leached and infertile soils, which require regular applications of fertiliser to maintain productivity. In south-western Australia, the majority of rainfall (70%) falls within a seven month growing period over a typically Mediterranean climate. Soils have formed from landscapes that are generally very old by world standards, are low in organic matter and nutrients, complex and highly variable. The most cost effective and beneficial option for DBC for the Water Corporation in Western Australia is through land application in agriculture, with approximately 14,800 t DS being applied to farms in 2004/05. The nitrogen (N) and phosphorus (P) in biosolids is used as a substitute for commercially applied fertiliser.

Western Australia has participated in the Australian National Biosolids Research Project (NBRP) since 2002 (McLaughlin *et al.* 2002). The research is conducted by Curtin University under the leadership of CSIRO Land and Water in Adelaide, South Australia. Other State research units exist in New South Wales, South Australia, Queensland and Victoria. The group's expertise centres on the impact of land applied biosolids on Australian soils and knowledge on how best to reuse these products of wastewater treatment in the context of the various issues raised by this practice http://www.awa.asn.au/Content/NavigationMenu/Information/SpecialInterestGroups/BiosolidsManagement/Biosolids_Management.htm.

Agricultural land application rates of biosolids are commonly applied at rates necessary to satisfy the crop nutrient uptake requirement of N, referred to as the nitrogen limiting biosolids application rate (NLBAR). In Western Australia, the NLBAR has been estimated at 8 t DS/ha for wheat, which is equivalent to 70 kg of plant available N ha⁻¹. Research data concluded that grain yield of wheat grown in biosolids at NLBAR were comparable to yields obtained using farmer rates of commercial inorganic fertiliser. Canola yields, however, were significantly higher ($P < 0.05$) in biosolids, substantiating the anecdotal yield increase claims by many farmers. Biosolids applied at NLBAR, resulted in soil concentrations in the surface (0-10 cm) well below the maximum allowable soil contaminant concentration (MACC) of metals such as zinc (Zn), copper (Cu) and cadmium (Cd) in the year of application (Pritchard & Collins 2005). The risk of pathogens transferring to cereal grains is under investigation (Crute *et al.* 2004).

A concern with using the NLBAR to determine land application rates is that the loading rate of P is higher than typically applied through a commercial fertiliser application, i.e. 180 kg P ha⁻¹. Excessive N and P have the potential to contaminate water bodies through runoff and/or leaching and lead to eutrophication of water bodies. Pritchard (2005) examined the impact of high loading rates of P in Western Australia following the application of biosolids at NLBAR in a number of glasshouse, field and laboratory experiments between 1999 and 2003. In the field, in the year of application biosolids were 68% as effective as inorganic P fertilisers as a source of P. In addition, the P in biosolids was of minimal risk of leaching in the current soils used for land application, and lower than for comparable rates of inorganic P fertilisers. Consequently the P limiting biosolids application rate (PLBAR) is under review to ensure crop requirements will be met (Pritchard and Penney 2003).

Forestry

Forestry plantations are a large potential market for biosolids use in Western Australia with 5,500 ha of softwood plantations south of Perth possibly suitable for the application of

biosolids. In plantations on the Swan Coastal Plain, the current fertiliser management usually includes the application of inorganic fertilisers of N and P at various stages throughout the rotation. The Department of Conservation and Land Management (DCLM) (now the Forest Products Commission FPC) has been investigating the response of pines to the application of biosolids since 1998, given the increases in tree growth following the application of biosolids in countries elsewhere.

Biosolids (DBC) were applied in 1998 to a 17 year-old *Pinus pinaster* plantation on deep Karrakatta sand in a 920 mm yr⁻¹ rainfall area, 120 km south of Perth. The experiment included a control, standard mineral fertiliser (500 kg ha⁻¹ di-ammonium phosphate + 250 kg ha⁻¹ urea) and two rates of biosolids applied at 17 and 34 t DS ha⁻¹. The experiment investigated the value of biosolids as a fertiliser replacement in plantations; assessed the potential for movement of pathogens, nutrients and heavy metals from the applied biosolids into groundwater beneath the highly permeable coarse sands; and determined operational constraints to the viability of routine biosolids applications.

Compared with the nil fertiliser control, the mineral fertiliser and both biosolids treatments initially increased the tree volume increment by 19%, 27% and 55%, respectively, over three years (2m³ ha⁻¹ yr⁻¹, 3m³ ha⁻¹ yr⁻¹, 6m³ ha⁻¹ yr⁻¹). The mineral fertiliser treatment produced the largest volume increment in the first year only relative to the control treatment. Relative volume increments in the biosolids treatments increased greatly in the second year and continued to increase in the third year, while the response in the MF treatment was constant and then declined. Biosolids applied at 34 t DS significantly increased foliar concentrations of N, P, zinc (Zn) and manganese (Mn) above all other treatments over three years. Both the mineral fertiliser treatment and biosolids treatment at 17 t DS significantly increased foliar concentrations of N for two years and P for three years above the control treatment (Dumbrell and M^cGrath, 2002). Eight years after start of the experiment, the trees in the biosolids treatments have continued to grow at a faster rate than the trees in both the nil and mineral fertiliser treatments, with the longevity of response yet to be determined. See the separate paper by Dumbrell (2006) within the proceedings of this conference.

Surface soil (0-10 cm) samples and groundwater did not detect any indication of pathogens (thermo-tolerant coliforms or salmonella), pesticides, and total N or P from any treatment. Concentrations of heavy metals in the 0-10 cm surface soil were less than the DEP *et al.* (2002) 1% MACC. The mineral fertiliser treatment was the only treatment to significantly (P<0.05) increase bicarbonate extractable P in the surface soil after treatment. Concentrations of nitrate in groundwater remained unchanged in samples taken from bores within the plantation. The nitrate was however, increased above acceptable limits for drinking water (ANZECC, 1992) in bore samples taken from beneath the stockpile area outside of the plantation at two sampling dates, eight months apart (Dumbrell and M^cGrath, 2003). It is suggested that trees within the plantation are either utilising all available nitrate within the soil profile or completely drying the soil profile so as to prevent recharge and nitrate movement to the groundwater. No attempt had been made to quantify total nutrient uptake by the trees.

The major constraints identified from this study relate to the high cost of transport and application, on site storage provisions, and the time required for stockpiling and application. The minor constraints were related to the social aspects, such as odour and public access, and the required operational condition of the plantation.

Composting

Companies in the Perth metropolitan area further process biosolids and produce products suitable for use in domestic markets. Approximately 2,400 t DS yr⁻¹ of DBC is transported direct from the WWTP and used in this market. In addition, processing a further 500 t DS @17% total solids is sourced from a temporary biosolids stockpile, which is slowly being depleted. Until recently the percentage of compost being utilised in areas such as horticulture and turf was minimal, however with changes to the availability of raw materials such as chicken litter, this market is also expanding.

There are many methods available for composting and blending material to produce a product that meets the market demands. However, a typical composting process can be divided into three distinct sections: initial blending of raw materials; windrowing to control temperature; and mixing and final blending. During the first stage, biosolids are blended with other products such as sawdust and green waste. The mix is windrowed for approximately 10 to 16 weeks, during which time the rows are turned at least twice a week. Once the biosolids mix has met the unrestricted use requirement (DEP *et al.* 2002), aliquots of the mix are taken and depending on market demand are blended with peat, sand, loams or mulch.

CONSTRAINTS TO BIOSOLIDS PRODUCTION

Vector attraction

Areas along the Swan Coastal Plain have reported excessive fly breeding over the past decade. Although all flies can be described as a nuisance, the one of most concern is the blood sucking *Stomoxys calcitrans* (stable fly). The stable fly, which prefers to breed in organic mediums including manures, has proved a particular menace in the regions of Wanneroo, Kwinana and Gingin (Penney and Dadour 2002). These fly epidemics have the potential to force the closure of the Water Corporations current programs for beneficial reuse of biosolids, typically land applied throughout the agricultural region.

In 2002, the Water Corporation commenced a project to determine the attractiveness and breeding capacity of flies in DBC over a 12-month period at the Nowergup Biosolids Facility, 30 km north of Perth. The project recorded the seasonal variation and response of fly breeding in fresh and aged DBC, identified the chemical and physical components that rendered biosolids attractive as a fly breeding medium by examining the relationship between the moisture level, pH, the ammonia content and specific organic content; and correlated the above information to determine guidelines for covering biosolids stockpiles and/or evaluated the potential for reducing the attractive factors through modification of WWTP operating procedures. The experiment supported previous studies that covering of the stockpiles during fly breeding season was the most effective control method and consequently have been implemented in the guidelines for the storage of biosolids. Alternatively minimising the stockpile time to less than 7 days also reduces fly breeding, however this is not always practical and is dependant on land availability.

Storage facility proposal

The Water Corporation has limited facilities to store DBC at the WWTPs with the current storage capacity of overhead hoppers of 150 to 300 t DS, which on average provide 36 hr holding. Biosolids are transported by truck and trailer to agricultural properties daily, which are unloaded and stockpiled in earthen bunds. Depending on the application area there may be several stockpiles scattered throughout the paddocks. There are a number of problems associated with stockpiling of biosolids, including the potential for nutrient rich leachate to contaminate groundwater and the attractiveness of the biosolids to vectors (flies). To minimise the environmental and public health impacts of stockpiling biosolids and for the continued success of the biosolids land application program, the Corporation has undertaken development of a Biosolids Storage Facility. This will be the first biosolids storage facility of its kind in Australia and possibly the world.

CONCLUSIONS

The positive benefits of biosolids as a fertiliser and a soil amendment have created a demand for a resource, which has often been 'wasted'. Research initiated by the Water Corporation in conjunction with Curtin University and the Forest Products Commission has targeted both agriculture and forestry as beneficiaries for the majority of DBC, with composting already established as a sound long-term market. Farmers have benefited from crop and soil improvement as a result of biosolids application with much anecdotal evidence and research data available to support this. Tree volume growth in pine plantations has increased significantly following biosolids application. Further research is required to establish the longevity of the increased growth within these coastal plantations. Under typical land application rates, no increases in N and P in ground water were measured on typically leaching coastal sands after three years beneath pine plantations. Laboratory studies showed that the solubility of P to be lower in biosolids amended soils compared with inorganic P fertiliser.

The agricultural land application rates are being fine tuned to ensure biosolids loading rates consider both the nutrient needs of the crop and the environmental risk. Consideration has been given to the unique soil and climatic conditions in Western Australia. Continuing research is being conducted in metal bioavailability and pathogens. The fly breeding program has highlighted solutions to prevent the breeding of flies in biosolids and influenced the design of the Biosolids Storage Facility. Overall, the use of biosolids, or 'black gold' as commonly referred to by farmers, has improved crop yields and increased sustainability within specific land use areas.

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Appendix 2

Summary of paper presented at the AWA: Biosolids Specialty III, Melbourne 2006

The response of wheat on acidic soil using lime-amended biosolids

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Key words

Lime-amended biosolids

Abstract

Approximately 70 tonne of lime-amended biosolids (LAB) is produced daily from the Subiaco Wastewater Treatment Plant (WWTP) in Perth. Soil acidity is an increasing problem in Western Australia. To date, no data is available as to the effect of LAB on soil pH in Western Australia. Lime-amended biosolids typically have a dry matter content of 35% and a total nitrogen (N) dry basis content of 3%. Thus, LAB is typically drier and lower in nutrients (except Ca) than dewatered biosolids cake (DBC) (5.0%N dry basis) due to a dilution of nutrients resulting from the addition of lime. The LAB is generally applied at similar land application rates to DBC compensate for the lower N. When applied at the nitrogen limiting biosolids application rate (NLBAR). This paper reports on a field experiment conducted to obtain information as to the neutralising value of LAB on soil acidity and to measure the growth of wheat.

At Subiaco, excess activated sludge from the secondary process flows to the Sludge Handling Building where it is thickened in the Dissolved Air Flotation Thickeners (DAFT). The thickened excess sludge is combined with Raw Sludge from the Primary Sedimentation Tanks and stored in the Sludge Blending Tank. The blended sludge is dewatered by centrifuge before the addition of lime (calcium oxide). Lime is added at a concentration of between 300 kg to 400 kg per dry tonne of sludge. Following the addition of lime the product is conveyed by screw to silos. Each silo is sampled and analysed for temperature, pH and total solids content.

The field experiment consisted of nine treatments comprising: three rates of LAB at 0.5xNLBAR, 1xNLBAR and 1.5xNLBAR (equivalent to dry t/ha); one rate of dewatered biosolids cake (DWC) at 1xNLBAR; four rates of lime at 0 t/ha, 2.3 t/ha, 4.6 t/ha and 6.9 t/ha (each with a basal fertiliser dressing of 100 kg urea/ha and 100 kg di-ammonium phosphate/ha); and a control (nil fertiliser). The experiment was arranged in a completely randomised block design with three replicates on a red-brown sandy loam. Shoot dry matter production at maximum growth (anthesis) and grain yield were measured for wheat (*Triticum aestivum*) as an indicator of nutrient availability.

Soil bicarbonate extractable P was increased by the addition of biosolids more so than pellets at comparable N loadings. However, it would be expected that P availability would be similar when biosolids/pellets were applied at comparable P loading rates. Wheat dry matter production in the field trial indicate a yield response to increasing rates of pellets, with the 4 dry t/ha most similar to

the district fertiliser practice and no yield response below the 4dry t/ha. This paper will include discussion of the grain results following the 2003 harvested. The results of this study will provide agronomic field data to better calculate land application rates of pelletised biosolids, combined with laboratory data to better understand their role in crop N and P nutrition.

Appendix 3

National Biosolids Newsletter Contributions, Western Australia
See weblink