Yield, Heavy Metal Content, and Milling and Baking Properties of Soft Red Winter Wheat Grown on Soils Amended with Sewage Sludge[1,2]

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ABSTRACT

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This study determined yield, metal content, and milling and baking properties of soft red winter wheat grown on soil treated with three municipal sewage sludges. Sewage sludge applications ranged from 56 to 448 tonnes/ha, levels in excess of those allowed by current federal regulations; the data, therefore, represent a worst-case situation. Sludge applications increased the protein content of wheat grain and flour and decreased alkaline water retention capacity of flour, but they did not affect test weight, thousand-kernel weight, and particle size index. Baking studies indicate that sludge applications decreased the baking quality of flour by increasing protein content, resulting in smaller-diameter cookies. Sludge applications also increased concentrations of zinc, cadmium, manganese, and nickel in wheat grain. Because the sludges applied contained $CaCO_3$, which increased soil pH, metal levels in wheat were not directly related to sludge-borne metals added to the soil. Concentrations of zinc, copper, nickel, cadmium, iron, and manganese were typically 5- to 10-fold greater in the bran than in the flour. Metal concentrations in the flour were nearly always less than those found in whole wheat grain with, on the average, $<24\%$ of the zinc, copper, nickel, cadmium, iron, and manganese in grain being recovered in the flour. The distribution of metals in the bran and flour was similar for wheat grown on sludge-treated and untreated soils.

One of the major considerations in applying municipal sewage sludges on agricultural land is the potential for increased concentrations of heavy metals in the human diet. Sewage sludges contain a variety of metals (Sommers 1977). Some are essential for plant and animal growth (eg, zinc, copper, iron, and manganese), but others are not essential in biological systems (eg, lead, mercury, nickel, and cadmium). Of particular concern has been elevated cadmium concentrations in the human diet, which could result from applications of sewage sludge on a significant percentage of U.S. cropland (U.S. EPA 1979). Because approximately 82% of the flour and cereal products consumed in the United States originates from wheat and its products, data are needed on metal uptake by wheat grown on soils amended with sewage sludge and also on the distribution of metals in wheat grain fractions obtained by milling processes.

The various metals applied to soils in sewage sludge differ in their availability to crops. Several reviews have summarized metal uptake by a range of crops (CAST 1976, 1980; Chaney and Giordano 1977; Chaney 1980; Sommers 1980; Logan and Chaney 1983). For a soft spring wheat, greenhouse studies using sewage sludge amended with salts of cadmium, zinc, nickel, and copper have shown that toxicity (decreased grain yield) in an acid soil increased in the following order: cadmium > nickel > copper > zinc (Mitchell et al 1978). The toxicities of zinc, copper, and nickel to wheat were similar in a calcareous soil. In both acid and calcareous soils, the concentrations of cadmium, zinc, nickel, and copper were greater in leaves than in grain and increased in direct proportion to the amount of metal applied to the soil. Greenhouse studies have also shown that cadmium uptake by soft spring wheat is intermediate, compared to uptake by leafy vegetables and corn (Bingham et al 1975). Wheat grain grown on strip-mined spoil treated with sewage sludge contained elevated concentrations of cadmium, zinc, copper, and nickel, but sludge applications had minimal effects on levels of manganese, iron, chromium, and lead (Hinesly et al 1979). Application of 44 tonnes of sewage sludge/ha has resulted in wheat grain levels of 1.42 mg Cd/kg, compared to 0.06 mg/kg for the untreated control (Baker et al 1979).

Cadmium is also found as a trace contaminant in phosphate fertilizers. The application to soils of diammonium phosphate containing 2–153 mg Cd/kg caused cadmium levels in wheat grain to increase from 0.014 to 0.086 mg/kg (Mortvedt et al 1981). In contrast, zinc concentrations in the grain decreased when phosphate was added, because the soil used had deficient phosphorus levels. In general, the concentrations of cadmium, zinc, and nickel in wheat grain can be increased by applying sewage sludge to soils, but the magnitude of the increase depends on the amount of metal applied and on such soil properties as pH.

Several studies have been done to evaluate the distribution of metals in the bran, shorts, and flour obtained from wheat grain by

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milling. In all cases, the germ, shorts, and bran were enriched in metals relative to the flour (Czerniejewski et al 1964, Toepfer et al 1972, Waggle et al 1967, Hinesly et al 1979, Mortvedt et al 1981). For example, the percentage of total metal found in the straight-grade soft wheat flour was 12, 26, 32, 50, 39, and 19% for manganese, zinc, nickel, cadmium, copper, and iron, respectively (Toepfer et al 1972). This study also found that metal concentrations could be greater in the final consumed product than in the flour added (ie, metals were added in shortening and other ingredients). Sewage sludge applications also result in elevated levels of cadmium, zinc, copper, and nickel in wheat grain, flour, shorts, and bran; metal concentrations in bran and shorts exceeded those in flour for all rates of sludge additions (Hinesly et al 1979). The cadmium and zinc concentrations in bran and shorts also exceeds those in flour for milled wheat grown on soils treated with the fertilizer, diammonium phosphate (Mortvedt et al 1981).

Proposed guidelines would limit the total amounts of lead, zinc, copper, and nickel that may be applied to agricultural cropland in sewage sludge (U.S. EPA 1983). Regulations were developed in 1979 to limit cadmium additions to cropland (U.S. EPA 1979). The metal limits are scaled to soil cation exchange capacity and range from 5 kg Cd/ha to 2,000 kg Pb/ha. To evaluate the applicability of the proposed metal limitations and to determine metal uptake by corn, soybeans, oats, and wheat, a field plot experiment was initiated in 1976, using sewage sludge from three Indiana municipalities. Sludge was applied once and then crop composition was evaluated each year to determine changes in the plant availability of metals. The concentrations of metals in oats (Kirleis et al 1981) and corn (Kirleis et al 1982) grown on the sludge-amended soils have been reported. Wheat grain samples were collected during the third cropping season after sludge addition (1979) and separated into bran and flour by laboratory milling. The objectives of this study were to evaluate the effect of sewage sludge additions on the cadmium, copper, zinc, nickel, iron, manganese, protein, and ash contents of wheat, bran, and flour, and to determine the baking qualities of the flour.

MATERIALS AND METHODS

Experimental Design

Field plots (four replicates in a randomized complete block design) were established in the fall of 1976 at the Purdue University Agronomy Farm on a Chalmers silty clay loam soil. Sewage sludges selected for study were obtained from sewage treatment plants in Anderson, Marion, and Frankfort, IN, and are designated as sludge numbers one, two, and three, respectively. Because these sludges contained elevated metal levels, significant increases in soil metal concentrations were obtained with single sludge applications, at rates ranging from 56 to 448 tonnes/ha (dry-weight basis). All sludges had been subjected to anaerobic digestion and then dewatered to approximately 50% solids on sand-drying beds or equivalent. The composition of the sewage sludges (dry-weight basis) is given in Table I, and the amounts of metals applied to the experimental plots at an application rate of 56 tonnes/ha are shown in Table II. The sludges were applied to the surface of 4.6 × 12.2-m plots and incorporated into the soil by plowing to a depth of 20 cm. The soil was a Chalmers silty clay loam (fine silty, mixed mesic Typic Haplaquoll) with the following properties: organic carbon, 2.3%; total nitrogen, 0.18%; cation exchange capacity, 23 meq/100 g; pH, 5.6.

Table I
Composition of Sewage Sludges[a]

	Source of Sludge		
	Anderson (Sludge no. 1)	Marion (Sludge no. 2)	Frankfort (Sludge no. 3)
Carbon (%)			
Organic	15.40	7.50	10.40
Inorganic	2.03	3.70	1.80
Nitrogen, organic (%)	0.68	0.66	1.42
Phosphorus (%)	1.38	0.85	1.89
Metals (mg/kg)			
Cadmium	284	247	1,210
Nickel	2,040	215	430
Zinc	6,800	5,200	1,900
Copper	1,200	450	1,300
Lead	1,070	1,520	3,480

[a] Dry weight basis.

Winter wheat (*Triticum aestivum* L., cv. Beau) was planted in the fall of 1977 and 1978 and harvested the following July. Wheat grain samples were collected from the 1979 harvest for the milling studies reported. Supplemental nitrogen fertilizer (90 kg urea-N/ha) was applied in early spring to all plots to maximize wheat yields. The grain samples were dried at 60° C for at least 48 hr and stored before analysis.

Wheat Quality Procedures

The test weight and thousand-kernel weight of the harvested grain was determined by AACC method 84-10 and by the method suggested by Dattaraj et al (1975), respectively. Wheat particle size index (PSI) was measured by modifying Yamazaki's procedure (Yamazaki 1972). The modifications included substituting a Stein shaker (model ZS, Fred Stein Laboratories, Inc., Atchison, KS) for the sonic sifter and screening 15 g of ground meal over a 425-μm-opening sieve for 30 sec. A 500-g subsample of wheat from each treatment was conditioned (14.5% moisture for 12 hr) and ground on a Brabender Quadrumat junior mill. The ground meal was screened over a 212-μm-opening sieve for 4 min on a Stein (model ZS) shaker to produce a straight-grade flour. The flour was tested for alkaline water retention capacity (AWRC) (Yamazaki and Donelson 1972b) and mixograph (70% fixed water absorption) mixing characteristics (AACC method 54-40) and was baked into cookies (Finney et al 1950).

Analytical Procedures

Protein content was determined by an automated Kjeldahl procedure (AOAC 1980), with titanium dioxide substituted for the mercuric oxide catalyst (Williams 1973). Ash and moisture contents were determined as described in AACC "Approved Methods" 08-01 and 44-40, respectively (1983).

For metal analysis, samples (2 g ± 0.01) of ground wheat (<40 mesh), bran, or flour were placed in 25 × 200-mm Pyrex tubes, treated with 10 ml of concentrated HNO_3, and maintained at room temperature for 16–20 hr. The samples were then placed in an aluminum block, initially at room temperature, and gradually heated to 130° C. Heating at 130° C was continued until approximately 0.25 ml of the HNO_3 remained. After cooling the samples, 3 ml of a 60% $HClO_4$:conc. H_2SO_4 (12:1, v/v) mixture were added and boiled gently in an aluminum block preheated to 210° C until the $HClO_4$ was completely evaporated. After cooling, the samples were diluted with deionized water to 10 ml. The digests were analyzed for cadmium, zinc, nickel, copper, iron, and manganese with a Varian AA-6 flame atomic absorption spectrophotometer. Background correction was used for cadmium and nickel analysis.

Appropriate controls and standards were prepared. All reagents used were analytical-grade, and solutions were prepared with distilled, deionized water. All glassware used for metal analysis was washed with 10% HNO_3 before use.

Table II
Metals Applied to Experimental Plots
at an Application Rate of 56 Tonnes/ha

	Metals Applied (kg/ha)		
Metal	Sludge no. 1	Sludge no. 2	Sludge no. 3
Cadmium	16	14	68
Nickel	114	12	24
Zinc	381	291	106
Copper	67	25	76
Lead	60	85	195

RESULTS AND DISCUSSION

The application of increasing amounts of sewage sludge to soil resulted in decreasing yields of wheat grain (Table III). The only exception to this trend was the 56 tonnes/ha application of sludge number one, which gave a slight but not statistically significant increase in yield. Compared to the untreated soil, a statistically significant yield decrease was caused by applying 224, 168, and 112 tonnes/ha for sludge numbers one, two, and three, respectively. These sludge application rates correspond to yield reductions of 26–43%. Similar reductions of 18–26% were previously observed for wheat grown in soils treated with metal salts and sewage sludge (Mitchell et al 1978). In view of the large amounts of metals added to the soil, it is likely that wheat yields were reduced through either a direct metal toxicity or a metal-induced iron or manganese deficiency (Chaney and Giordano 1977, Chaney 1980, Mitchell et al 1978). Even though sludge applications reduced wheat yields, there were only minimal effects on the test weight and thousand-kernel weight of the grain (Table III).

The protein content of wheat grain was increased by nearly all rates of sewage sludge application (Table III). For all three sludges, the protein content was directly related to the application rate and was inversely related to grain yield. Significant increases in protein were found at application rates of 112, 112, and 56 tonnes/ha for sludge numbers one, two, and three, respectively. Unimpaired nitrogen uptake and decreased dry matter accumulation could explain the increased grain protein content. Adequate nitrogen availability was ensured by applying urea in early spring to supplement the inorganic nitrogen released by decomposing organic nitrogen in sewage sludges.

Ash contents were 1.90–2.12% (Table III). For the majority of treatments, ash content was similar in wheat grown on untreated and sludge-treated soils.

A grain property considered important in soft wheat quality is kernel texture, as measured by PSI. The degree of fineness of a wheat meal, as determined by the PSI test, is associated with cake baking potential (Yamazaki and Donelson 1972a) and with break flour yield (Yamazaki and Donelson 1983). Data show that sludge application did not affect PSI values (Table III), but as shown in Table IV, sludge application rates of more than 56 tonnes/ha did affect flour yield. Significant decreases in flour yield resulted when application rates were equal to or greater than 224, 168, and 112 tonnes/ha for sludge numbers one, two, and three, respectively. The greatest decrease in flour yield (approximately 3%) occurred at application rates of 168 and 448 tonnes/ha for sludge numbers three and one, respectively.

The ash contents of flour and bran were not significantly affected by growth of wheat on soils treated with sewage sludge (Table IV). In contrast, the flour protein content was higher for nearly all rates of sewage sludge applications (Table IV). The increases in flour protein parallel the increases in wheat grain protein resulting from sludge treatments. The patterns of change in bran protein and ash were similar to those for flour protein and ash (Table IV). A flour parameter associated with cookie spread in soft wheats is alkaline water retention capacity or AWRC (Yamazaki and Donelson 1972b). The higher the AWRC value, the smaller the cookie spread. Regardless of the sludge treatment, flour AWRC values were significantly lower than for flour milled from wheat grown on untreated soil (Table IV). Accordingly, the cookie spread (diameter) of flour derived from wheat grown on sludge-treated

Table III
Effects of Sewage Sludge Application on the Yield, Test Weight, Thousand-Kernel Weight (TKW), Protein, and Ash Contents, and Particle Size Index of Wheat[a]

Sludge Application		Yield[b] (Tonnes/ha)	Test Weight (kg/ha)	TKW[b] (g)	Protein ($N \times 5.7$)[b] (%)	Ash[b] (%)	Particle Size Index (%)
No.	Rate (Tonnes/ha)						
None	···	5.26 ab	62.0 a	41.6 ab	14.0 a	1.97 bcde	49.1 abc
1	56	5.59 a	61.8 a	41.6 ab	14.0 a	2.06 efg	46.6 a
	112	4.40 bcd	61.3 abc	41.6 ab	15.2 b	2.11 fg	47.3 ab
	224	3.55 de	61.0 bc	40.6 bc	16.7 d	2.12 g	49.1 abc
	448	3.78 de	61.0 bc	41.6 ab	17.3 e	2.01 cdef	50.6 bc
2	56	5.15 ab	61.8 a	40.4 bc	14.2 a	1.93 abc	48.5 abc
	112	4.80 abc	61.7 ab	40.7 bc	15.4 bc	1.95 bcd	51.8 c
	168	3.89 cde	61.8 a	39.8 c	16.2 d	1.85 a	50.2 bc
3	56	4.38 bcd	61.6 ab	42.6 a	16.1 d	1.90 ab	51.1 c
	112	3.02 e	60.8 c	42.4 a	17.1 e	2.04 defg	50.3 bc
	168	2.93 e	61.1 bc	41.5 ab	17.1 e	2.04 defg	49.4 ac

[a] Values in a column followed by the same letter are not significantly different ($p = 0.05$) by Duncan's multiple range test.
[b] Values reported on a dry weight basis.

Table IV
Effects of Sewage Sludge Application on Wheat Milling and Flour Baking Quality[a]

Sludge Application		Flour Yield (%)	Protein ($N \times 5.7$) (%)[b]		Ash (%)[b]		AWRC (%)	Cookie Diameter[c] (cm)	Mixograph Properties	
No.	Rate Tonne/ha)		Flour	Bran	Flour	Bran			Peak Height (mm)	Peak Time (min)
None	···	65.6 a	12.4 a	19.1 ab	0.50 bc	4.62 b	57.4 a	17.7 ab	46.3 a	4.0 a
1	56	65.0 a	12.7 a	19.2 ab	0.53 d	4.85 cd	56.6 bc	17.6 abc	49.7 a	3.4 bcd
	112	64.4 abcd	13.6 b	19.7 bc	0.55 d	4.74 bcd	56.5 bc	17.3 d	56.1 bc	3.8 ab
	224	63.4 bcde	15.3 cd	21.4 d	0.54 d	4.92 d	56.2 bcd	16.8 f	60.6 cd	3.0 efg
	448	62.7 e	15.6 d	21.3 d	0.52 cd	4.52 b	56.6 bc	16.9 f	63.0 d	2.7 g
2	56	64.7 ab	12.6 a	19.0 a	0.49 abc	4.65 bc	55.5 cd	17.8 a	47.3 a	3.4 bcd
	112	64.5 abc	13.6 b	20.0 c	0.48 ab	4.66 bc	55.0 d	17.4 cd	55.7 b	3.1 def
	168	63.0 de	14.5 c	21.0 d	0.47 a	4.32 a	55.8 bcd	17.3 d	55.5 b	2.9 fg
3	56	65.1 a	14.8 cd	20.8 d	0.49 abc	4.60 b	57.0 b	17.2 de	58.0 bc	3.5 bc
	112	63.1 cde	15.7 d	21.0 d	0.52 cd	4.70 bc	56.3 bcd	17.0 ef	58.4 bcd	3.4 bcd
	168	62.7 e	15.7 d	21.4 d	0.50 bc	4.62 b	55.8 bcd	16.9 f	60.6 cd	3.3 cdef

[a] Values in a column followed by the same letter are not significantly different ($p = 0.05$) by Duncan's multiple range test.
[b] Values reported on a dry weight basis.
[c] Diameter of two cookies.

soils should be greater than flour milled from the control wheat. However, unlike the effect predicted by AWRC values, nearly all flour samples from sludge-treated plots yielded cookies with smaller (undesirable) diameters than did the flour from untreated plots (Table IV). This reversed trend may be a result of the higher protein content of the flour milled from wheat grown on sludge-treated soils. The linear correlation coefficient between flour protein content and cookie diameter was $r = -0.955$ (significant at $p = 0.05$), whereas the relationship between AWRC and cookie diameter was $r = 0.016$. Thus, in this study, cookie diameters were influenced more by protein content than by alkaline water absorption.

The mixograph characteristics of the flour-water fixed absorption doughs for wheat grown in sludge-treated and untreated soils are shown in Table IV. The effects of increased flour protein, caused by sewage sludge application, on the dough mixing characteristics are striking. Peak heights of the high-protein flours are much higher than that from the low-protein flour from untreated plots. The protein content also influenced the time required for the curve to reach the peak (peak time). As flour protein content increased (as a result of sludge treatment), the peak times decreased. The observed influence of flour protein content on dough mixing characteristics agrees with results reported by Swanson (1940).

The conclusion from the milling and baking quality tests is that sewage sludge treatment affects the milling properties of wheat only at high levels of sludge applications. The baking quality of the flour was decreased as a result of growing wheat in soils treated with sludge above 56 tonnes/ha. The poor baking quality of the flour appears to be a result of the increased protein content of the wheat grain grown on sludge-treated soils.

The effect of sludge application on the zinc, cadmium, copper, nickel, iron, and manganese contents of wheat, bran, and flour is shown in Table V. Sewage sludge applications resulted in significant increases of zinc, cadmium, nickel, and manganese in wheat grain. In general, the increase in metal concentrations paralleled the amount of metal applied to the soil for a given sludge. Because the sludges contained variable amounts of calcium carbonate that increased soil pH (eg, 5.8 to 7) and because metal availability to plants is reduced at a neutral pH (CAST 1976, 1980), a direct correspondence was not found between the metal levels in wheat and the amount of sludge-borne metals applied to the soil. The increase in soil pH may explain the minimal effect of sludge applications on iron concentrations in wheat (Table V). There was also a tendency for copper concentrations in wheat grain grown on most sludge treatments to be less than or equal to those from untreated plots. The concentration ranges found in wheat grain were: zinc, 37.3–71.4 mg/kg; cadmium, 0.60–4.56 mg/kg; copper, 3.8–5.6 mg/kg; nickel, 0.6–5.7 mg/kg; iron, 29.8–43.2 mg/kg; and manganese, 3.96–14.3 mg/kg.

The metal concentrations in the bran always exceeded those found in the flour (Table V), typically by a factor of 5 to 10. In both bran and flour, metal concentrations generally increased with higher amounts of sludge applied. The results obtained are very similar to those of Hinesly et al (1979) with respect to the effect of sludge applications on the metal content of grain, bran, and flour and the distribution of metals in bran and flour. The metal concentrations in flour were: zinc, 5.3–8.9 mg/kg; cadmium,

Table V
Concentrations of Zinc, Cadmium, Copper, Nickel, Iron, and Manganese in Whole Wheat, Bran, and Flour[a]

Sludge Application		Concentration (mg/kg) in					
No.	(Rate (Tonnes/ha)	Whole Wheat	Bran	Flour	Whole Wheat	Bran	Flour
			Zn			**Cd**	
None	...	37.6 a	76.8 a	6.0 ab	0.60 a	1.20 a	0.41 a
1	56	49.9 cd	96.2 cd	7.2 abc	1.09 ab	2.98 bc	0.57 a
	112	51.2 cd	93.0 bc	8.9 c	1.48 bc	3.97 c	0.63 ab
	224	57.5 f	112.0 efg	8.8 c	1.90 cd	5.25 d	0.81 b
	448	71.4 g	143.0 h	7.4 abc	2.30 d	5.75 d	0.84 b
2	56	37.3 a	86.5 b	5.3 a	0.65 a	2.13 ab	0.58 a
	112	44.6 b	107.0 ef	6.6 abc	0.70 a	2.10 ab	0.45 a
	168	48.1 bc	103.0 de	7.1 abc	0.74 a	2.17 ab	0.51 a
3	56	53.0 cde	112.0 efg	7.6 abc	3.74 e	9.85 e	1.38 c
	112	54.2 ef	116.0 efg	8.3 bc	4.41 f	10.88 ef	1.59 d
	168	54.1 def	118.0 g	8.0 abc	4.56 f	11.50 f	1.69 d
			Cu			**Ni**	
None	...	4.4 bc	10.0 abc	0.96 a	1.0 ab	2.5 a	0.8 bc
1	56	4.7 cd	10.4 bc	1.29 b	1.7 cd	4.0 bc	0.8 bc
	112	5.1 de	9.5 abc	1.34 b	2.1 d	4.9 c	0.2 ab
	224	5.5 e	9.21 ab	1.45 bc	3.2 e	7.5 d	<0.1 a
	448	5.6 e	12.2 d	2.64 g	5.7 f	14.7 e	<0.1 a
2	56	3.8 a	10.9 cd	1.72 de	1.0 ab	2.6 a	0.4 abc
	112	3.8 a	10.0 abc	1.54 c	0.8 ab	2.1 a	0.9 c
	168	3.9 a	9.49 abc	1.55 cd	0.6 a	2.2 a	0.5 abc
3	56	3.9 a	9.72 abc	2.06 f	1.2 abc	3.2 ab	0.7 bc
	112	4.0 ab	9.10 ab	1.86 e	1.4 bc	3.3 ab	0.6 abc
	168	3.8 a	8.67 a	1.6 cd	1.4 bc	3.6 abc	0.4 abc
			Fe			**Mn**	
None	...	29.8 a	55.4 e	8.88 ab	3.96 a	10.90 cd	2.79 c
1	56	33.7 c	55.1 e	8.69 ab	4.64 ab	11.80 cd	1.71 b
	112	40.0 d	58.3 ef	9.72 abcd	5.15 ab	10.20 abc	1.67 b
	224	43.2 e	59.5 f	11.20 d	5.02 ab	8.79 ab	1.13 a
	448	29.9 ab	51.4 d	9.82 abcd	5.34 ab	8.25 a	1.04 a
2	56	31.0 ab	42.7 b	8.27 a	8.87 c	22.00 f	1.32 ab
	112	32.0 abc	12.2 a	10.4 bcd	14.30 d	12.40 d	1.36 ab
	168	32.1 bc	12.4 a	9.22 abc	7.51 bc	11.80 cd	1.05 a
3	56	31.5 abc	48.1 cd	10.9 cd	6.32 abc	10.60 bcd	1.09 a
	112	31.1 ab	47.1 c	9.77 abcd	6.52 abc	19.20 e	1.20 a
	168	33.6 c	13.0 a	9.37 abc	7.09 bc	10.40 bcd	1.00 a

[a] For each parameter, values in a column followed by the same letter are not significantly different ($p = 0.05$) by Duncan's multiple range test; all data are on a dry-weight basis.

0.41–1.69 mg/kg; copper, 0.96–2.64 mg/kg; nickel, < 0.1–0.9 mg/kg; iron, 8.27–11.2 mg/kg; and manganese, 1.04–2.79 mg/kg. With the exception of cadmium, these concentrations are within the ranges presented for wheat flours by Czerniejewski et al (1964), Toepfer et al (1972), and Waggle et al (1967). Cadmium concentrations in wheat flour were not increased by application of sludge number two even though 14–42 kg Cd/ha were applied. In contrast, applications of sludge numbers one (56 tonnes/ha = 16 kg Cd/ha) and three (56 tonnes/ha = 68 kg Cd/ha) resulted in significant increases in flour cadmium. Current regulations (U.S. EPA 1979) limit cadmium additions to 20 kg/ha for the soil used in this study (ie, approximately 60 tonnes/ha for sludge numbers one and two and 25 tonnes/ha for sludge number three). In addition, the cadmium content of wheat grown on untreated plots was 0.60 mg/kg, whereas most studies report values of <0.1 mg/kg. This difference may be related to the indigenous cadmium level in the soil, an acid soil pH (5.8), and the cultivar of wheat grown.

The metal data in Table V and the flour yield in Table IV can be used to assess the distribution of metals in bran and flour. Except for nickel, for which nondetectable levels limit such calculations, the distributions in the flour are 12, 16, 19, 23, and 24% for zinc, manganese, iron, cadmium, and copper, respectively. In a similar study, Hinesly et al (1979) reported that the proportion of metals in the flour ranged from 14% for zinc to 43% for manganese. Sewage sludge applications did not cause a marked change in the proportion of metals found in the bran and flour. Thus, the effect of sludge applications on the metal content of flour used in the human diet can be approximated from a knowledge of the wheat grain metal content and a constant distribution function.

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