Characterization of Compost Produced at a Golf Course: Impact of Historic Mercury Accumulations In Putting Green Soil

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This paper reports on the physical and chemical properties of feedstock and compost materials used at the Clear Lake Golf Course located in southwestern Manitoba. The compost was found to have a very low organic matter content (range = 9.1 to 13.2%) and a low moisture content (27.8 to 32.8%). To improve the compost quality, two recommendations were made: (1) a composting pad should be installed to prevent soil contamination and (2) the moisture content should be monitored, particularly during the curing stage. The compost contained Hg concentrations ranging from 3.16 to 6.1 mg kg^{-1}. The grass clippings, the primary feedstock material, had Hg concentrations ranging from 8.53 to 20.2 mg kg^{-1}. The putting green soil Hg concentration ranged from 60.7 to 90.8 mg kg^{-1}. Elevated Hg levels may have been due to previous mercurial fungicide use and all the values were well above the Canadian compost and soil guideline values of 0.8 and 6.6 mg kg^{-1}, respectively. It was estimated that 104.4 kg of Hg has accumulated in the top 8 cm of the putting green soil, which cover an area of 9,290 m^2. Based on a Hg flow analysis conducted on the solid materials entering and leaving the putting green soil, a passive remediation approach was recommended that involved: (1) removal of the aeration cores, (2) restrictions on the compost use, (3) construction of a composting pad, and (4) the periodic monitoring of the soil and compost Hg concentrations. Calculations suggested the soil would reach the soil quality guideline value in approximately one hundred years. This is a long period of time, and, as the data suggests a degree of bioavailability, the impact of the long-term exposure to golf course staff must be determined. As there are thousands of golf courses in North America that may have been treated with mercurial fungicide, a health risk assessment should be done on the Hg exposure levels during the handling and processing of the aeration cores and grass clippings.

Introduction

In North America, there is considerable interest in evaluating and mitigating the negative environmental impacts of golf course operations (Anon. 1996; RCGA 1993). In this regard, part of the Canadian National Agricultural Compost Trials (NACT), initiated in 1996, included a case study of the Clear Lake Golf Course (CLGC) . The general goals of the NACT were to demonstrate and quantify the benefits of compost use (Simard 1995). The specific, long-term goals of the case study at the CLGC were to characterize the current organic waste management system and to evaluate various compost use strategies on turf grass. The purpose of this paper is to present the physical and chemical properties of the various compost materials used at this operation and to discuss the implications of elevated mercury levels found in the compost.

The benefits of composting organic materials at golf courses are well documented and can be grouped into three general categories: waste reduction, decreased operating costs, and enhancement of turfgrass health. A significant component of the total

solid waste stream at a golf course consists of compostable organics. The organic fraction (excluding paper) was found to represent 88% of the total solid waste stream at the Clear Lake Golf Course (McCartney *et al.* 1998). The grass clipping generation rate was 2.27 tonnes per week (113.4 kg green^{-1} week^{-1}), representing 93.9% of the organic fraction (unpublished data, McCartney). The remaining 6.1% (0.15 tonnes per week) came from kitchen waste. In a typical North America golf course operation, grass clippings are collected from the greens, and, in some cases, from the fairways. Traditionally, the clippings are disposed of by dumping and spreading on the ground (fairways, roughs, or bush), in municipal landfills, or in dedicated dumps located at the golf course (Witteveen 1989). Composting has only recently been seen as a viable alternative at North American golf course operations (Witteveen 1989). Passios (1991) reported a 50 to 74% reduction in soil costs due to on-site composting operations at the Hyannisport Golf Club, Cape Cod.

The benefits of compost use on soil fertility, in general, and for turfgrass growth, in particular, are well documented (Sikora and Enkiri 1999; Carey and Gunn 1998; Nelson 1996; Dinelli 1999; Breslin 1995; Wilkinson 1994; Dick and McCoy 1992). The benefits are related to increases in organic matter (biomass such as earthworms, insects, and microorganisms and humic materials) which in turn improve soil structure, fertility, water holding capacity, encourages plant growth-promoting substances, soil organism biodiversity, and disease suppression (Dinelli 1999; Nelson 1996; Wilkinson 1994). As compared to commercial fertilizers, however, composts are low in nitrogen content, difficult to store and apply, expensive, and in some cases contaminated with salts, heavy metals, and weed seeds (Dubble 1999). Nelson (1996) reported that composts are one of the most consistent and predictable biocontrol disease suppression products and Nakasaki *et al.* (1998) recently reported on a bench-scale composting method that produced a disease suppressive compost from grass clippings and a suppressive inoculum.

Several researchers have reported on high levels of mercury that have accumulated in golf course soils due to the historic use of mercurial fungicides (Byrtus 1998; Fushtey 1982; Gilmour and Miller 1973; MacLean *et al.* 1973). In Canada, the most common fungicide used at golf courses, Calo-clor®, was first registered in 1949 and manufactured until 1993, while all mercurial fungicide registrations were discontinued in 1995, with sales allowed until December 1997 and usage permitted until December, 2000 (Byrtus 1998). Undoubtedly many other mercurial fungicides were used. A table presented in Diltri (1972), listed over one hundred and fifty different mercurial fungicides that were listed in a pesticide handbook published in 1970. Calo-clor® consists of 60% mercurous chloride (Hg_2Cl_2) and 30% mercuric chloride ($HgCl_2$) and the recommended application rate is 0.6 g m^{-2} yr^{-1} (Gilmour and Miller 1973). Byrtus (1998) estimated that one application of Calo-Clor® would be enough to exceed the current Canadian Soil Quality Guideline value of 6.6 mg kg^{-1}. Interestingly, Fushtey (1982) commenting on the impacts to the environment suggested the mercurial fungicides were safe as the Hg did not move into ground or surface waters. The comments suggest that researchers twenty years ago did not consider the soil and air environments. With the recent release of compost and soil quality guidelines in Canada soil impacts can no longer be ignored. A summary of the Canadian Compost and Soil Quality Guidelines and the ranges of heavy metal concentrations found in commonly applied soil amendments (Alloway 1990) are presented in Table 1.

The Clear Lake Golf Course (CLGC) is located in Riding Mountain National Park, just east of Clear Lake in southwestern Manitoba. The course typically operates from May until mid-October. The total area of the golf course is 73.37 ha. Two types of composting are currently used on-site. The first is composting toilets, which treat human

TABLE 1.

A comparison of the typical ranges of heavy metal concentrations (Alloway 1990) to CCME's Environmental Quality Guideline values for compost and soil.

Metal	Agricultural Soil	Manure	Compost concentration ($\mu g\ g^{-1}$)	Compost Category A (CCME 1996)	Soil Agriculture (CCME 1997)
Arsenic	1-20	3-25	2-52	13	12
Cadmium	0.2-1	0.1-0.8	0.01-100	3	1.4
Chromium	70-100	1.1-55	1.8-410	210	64
Cobalt	10	0.3-24	NR[a]	34	40
Copper	20-30	2-172	13-3580	100	63
Lead	10-30	1.1-27	1.3-2240	150	70
Mercury	0.03-0.06	0.01-0.36	0.09-21	0.8	6.6
Molybdenum	1-2	0.05-3	NR	5	5
Nickel	50	2.1-30	0.9-279	62	50
Selenium	0.5	2.4	NR	2	2
Zinc	50	15-566	82-5894	500	200

Notes: [a] NR = not reported.

excrement. The second is a windrow composting operation. The windrow operation will be discussed in this study. The windrow facility is located on a soil surface on the golf course property. Feedstock consists of grass clippings from the twenty putting greens (eighteen holes plus the practice and nursery greens), source-separated kitchen waste from the concession operations and staff buildings, and straw, which is used as an amendment. No preprocessing of the feedstock material takes place.

Turfgrass on the greens consists of approximately 80% Annual bluegrass (*Poa annua*) and 20% Creeping bentgrass (*Agrostis palustris*). The greens are mowed to a height of 4 mm (7/32 inch) every day. The greens receive water daily either through natural precipitation or by an irrigation system. Grass clippings are stored in clipping boxes and every three or four days the clippings are collected and added to the active compost pile. It was estimated that 39 wet t of grass clippings are generated at the CLGC each year (McCartney *et al.* 1998). The fairway clippings are left on the fairway. Averaging 5,000 ft^2 per green, the twenty greens cover an area of 100,000 ft^2 (9,290 m^2). The greens are hollow core aerated once each year using 1/2 inch (12.7 mm) inside diameter hollow tines. The cores are removed from the greens. During the year the greens are topdressed at a rate of 0.6 yd^3 1000 ft^{-2} y^{-1}. This material consists of the compost produced at the golf course plus a topdressing mixture of sand, soil, and peat at a volumetric ratio of 50:40:10.

The kitchen waste collected on-site consists mainly of food waste generated during meal preparation at the club house restaurant. Egg cartons are also added to this waste stream, however, linen napkins are used in the restaurant so very little other paper product material is present in the waste stream. The kitchen waste is stored and once every two or three days it is collected and added to the active compost pile. It was estimated that 3 wet t of kitchen waste are collected each year (McCartney *et al.* 1998).

Straw, stored at the composting site, is added with the grass clippings and kitchen waste when forming a new compost pile. It was estimated that 4 wet t of straw are added as feedstock amendment each year (Holden, unpublished data).

Each new compost pile receives material for approximately half of the operating season resulting in two piles formed each year with each pile containing a volume of approximately 6 m^3. The piles are periodically turned, but no records of turning fre-

quency are kept. It was estimated that the piles were turned once every two weeks. The compost is used after two years.

Materials and Methods

Compost Material Samples

Two compost piles were sampled before screening. One pile was formed during the summer of 1995 and sampled June, 1997. The second pile was formed in the summer of 1996 and sampled November, 1997 and June, 1998. In general, the compost sampling methodology followed that recommended in CAN/BNQ (1997). Dice were used to generate all random numbers. All samples were stored in ziploc plastic bags or HDPE pails at 4°C. When sampling the 1995 pile, the pile was divided into ten equal sections. A subsample of approximately 3 L was randomly collected from either the top, middle, or bottom portion of each section. The subsamples were mixed thoroughly to yield a total sample volume of approximately 30 L. Quartering was used to reduce the sample size until each quarter equalled approximately 2 L. Three of the quarters were randomly selected for analysis.

Before sampling, the length, width, and height of the 1996 pile were recorded and the volume of the pile was calculated using the formula:

$$V = \frac{2}{3} h w (l - w) + \frac{1}{3} \pi h \left(\frac{w}{2}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where h, w, and l = the pile height, width, and length, respectively. The 1996 pile was sampled three times. The subsamples of the first sample were combined, mixed, and quartered to yield four replicate samples of approximately 3L each. These were designated samples 96-A, -B, -C, and -D. The subsamples of the second sample were combined and mixed, but were not quartered, resulting in a sample volume of approximately 30 L. This sample was labelled 96-E. The third sample was collected as per sample 96-E and labelled sample 96-F. Samples 96-A to 96-E were collected in November, 1997, while sample 96-F was collected in June, 1998.

The straw sample was collected from a portion of a single round bale that had been spread to a depth of approximately 30 cm. Ten subsamples of approximately 3L each were randomly selected from a grid containing thirty equal sections. The subsamples were combined, mixed, and quartered until each quarter consisted of approximately 2 L. One of the quarters was randomly selected for analysis.

The kitchen waste (KW) material was collected over a period of three days. As the KW material was very heterogeneous, a size reduction step was added to the quartering procedure. Before the initial quartering, the individual particles of the entire 63 kg sample were reduced to ≤ 3 cm by tearing, cutting, or chopping the material. After a thorough mixing, the sample was quartered twice to yield a sample size of approximately 16 kg. The particles were then further size reduced to ≤ 1 cm. This material was then thoroughly mixed and quartered twice to yield quarters of approximately 1kg each. One of the quarters was randomly selected, blended using a food processor, sealed in a ziploc bag, and stored at 4°C. Clean stainless steel equipment was used for all particle size reductions.

Grass samples were collected from the clipping boxes over a period of three days. The clippings were transferred from clipping boxes to 83-L or 68-L plastic Rubbermaid

containers using steel shovels that had been thoroughly cleaned to reduce contamination. A 1 L subsample was taken from each 83-L or 68-L container (32 subsamples in total). Subsamples were combined, thoroughly mixed, and quartered until four quarters of approximately 2 L each remained. Three quarters were randomly selected and designated as samples Grass-A, -B, and -C.

Soil Samples

Soil samples were collected from an 2 m by 12 m area located on the practice green, and from an 2 m by 24 m area located on the fourth fairway. For the green, seven samples were collected following a zigzag pattern from each of four 2 m by 3 m blocks. The seven samples were combined to give one composite sample per block and the samples were designated as Green-A, -B, -C, and -D. Seven fairway soil samples were collected in a zigzag pattern over the entire plot. In both cases, the soil was sampled to a depth of 15 cm. Fairway soil bulk densities were determined in triplicate using standard *in situ* cylinders (V=90.5 mL) at a depth of 8 cm.

To determine amounts of soil removed during hollow core aeration the number of cores and depth of cores were measured. After aeration, four one metre square plots were randomly selected from within the practice green research area and the number of holes m^{-2} recorded for each plot. Eleven holes were randomly selected from four plots and the depth of each hole was recorded. The inside diameter of the hollow core tines was 1/2 inch (12.7 mm). The total volume of soil removed in the aeration cores was calculated as:

$$V_a = \pi \left(D/2 \right)^2 d\, x \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

where D = the inside diameter of the hollow core tine (1.27 cm), d = the depth of the core (cm), and x = the number of cores per unit area (cores $m^{-2}\, y^{-1}$).

Analytical Methods

The pH and electrical conductivity (EC) were measured using electrodes on saturated paste. Moisture content analyses (dried at 100°C) were done on four replicate samples of grass clippings, straw, and kitchen waste. Total organic carbon (TOC) and total nitrogen (TN) were measured using a Leco CHN 600 combustion furnace. Both the organic matter (OM) and the carbon to nitrogen ratio (C:N) were calculated from TOC and TN data. NH_4-N, $NO_{2/3}$ N, and SO_4-S were extracted with $CaCl_2$ and measured using automated colorimetry (APHA 4500 NH_3:G; APHA 4500-NO_3 :E; APHA 4500-SO_4:F). Available K and PO_4-P were extracted with ammonium acetate/acetic fluoride and measured using automated molybdate colorimetry (APHA 4500-P:E) and flame photometry (APHA 4500-K:D), respectively. Available Ca, Mg, and Na were extracted with ammonia acetate and measured with inductively coupled plasma (ICP; US EPA 6010).

Samples for trace element analyses were spread on non-metalic pans and dried at 40°C. When dry samples were disaggregated using a mortar and pestle. Non-compostable components >1cm were removed and the entire sample passed through a 4.75mm sieve. A 200 g sample was prepared using the quartering method and then ground or sieved to < 2mm and stored in PET500 jars. Total elements (Al, As, Sb, Ba, Be, Bi, Cd, Ca, Cr, Co, Cu, Fe, Pb, Li, Mg, Mn, Mo, Ni, P, Se, Ag, Si, Sr, Tl, Ti, Sn, V, and

Zn) were measured using ICP atomic spectroscopic analysis (ICP-AES; US EPA 6010) following nitric/hydrochloric acid digestion (US EPA 3050A). Total mercury was measured by cold vapor atomic absorption (APHA 3112B) using the same extract.

Compost particle size distribution was determined on sample 96-D by sieving through 12.7 mm (1/2 inch), 6.35 mm (1/4 inch), and 3.18 mm (1/8 inch) screen sieves using a Ro-Tap Testing Sieve Shaker No. 12216. Sample 96-E was analyzed for particle size distribution by sieving through 12.7 mm (1/2 inch), 9.53 mm (3/8 inch), 6.35 mm (1/4 inch), and 3.18 mm (1/8 inch) and 1.59 mm (1/16 inch) screen sieves and the same shaker.

The bulk density of the 1996 pile was determined both *in situ* and on disturbed samples. The *in situ* determinations were done by cutting a 1m wide section through the pile with a bucket loader. Standard *in situ* soil bulk density cylinders (V = 90.5 mL) were then inserted into the exposed face of the pile at depths of 0.15, 0.45, 0.8, and 1.05 m. The total pile height was 1.2 m. Four replicates were taken at each depth. Gravimetric moisture content (MC) determinations (dried at 100°C) were made of samples.

Disturbed sample BD determinations were done in two ways: the large container method was used for storage calculations and as a comparison to the *in situ* measurements, while the other method was used for topdressing calculations. For the large container method the compost pile was divided into eight equal sections. Subsamples (3L each) were then systematically collected from the top, middle, and bottom of each section. The subsamples were mixed thoroughly to yield a final sample volume of approximately 60 L. A large, 83-L Roughtote Rubbermaid, container was calibrated to an inside lip (V = 56.93 L) and the tare weight recorded. The container was filled with a sample in three lifts. After each lift the container was agitated by hand, first by rotating back and forth three times, and then by lifting the container approximately 10 cm off the ground and dropping three times. After the third lift the material was made level with the internal lip using a $1 \times 2 \times 12$ inch stick. The weight of the compost and container was recorded (±0.1kg). The bulk density was calculated as the weight of compost divided by 56.93 L.

The topdressing BD were determined on material that passed a 6.35 mm (1/4 inch) screen. Sample 96-F was passed through a 6.35 mm (1/4 inch) screen and then quartered. BD determinations were done using standard 140 mL bulk density containers. Four replicates were analyzed.

Results and Discussion

The results of the CLGC compost material characterization are presented in Tables 2 to 8. Most of the general chemical properties reported in Table 2 fall within typical ranges reported for yard waste composts, except for the low fertility and the low organic matter content. This was surprising given the high organic matter content of the individual feedstock materials. Epstein (1997) reported, in general, organic matter in compost varies from as low as 30% to a high of 70%, while the organic matter in the CLGC compost ranged from 9.1 to 13.2%.

The results of the total element concentrations found in the composts and the feedstock material are presented in Tables 3, 4, and 5. All discussion of metal content in this paper will be based on the mass of an element found per unit of dry matter. For all samples, the results for Antimony (Sb), Bismuth (Bi), and Thallium (Tl) were below the method detection limits of 0.5, 0.7, and 0.4 mg kg^{-1}, respectively, therefore these data were not presented. The elements listed in the Canadian Compost Quality Guidelines (CCME 1996) are presented in Tables 3 and 4, which also include the soil results.

TABLE 2.
Chemical properties of the 1995 and 1996 finished composts
and the individual feedstock materials

Sample Description		pH	EC (mS cm^{-1})	C (%)	OM (%)	TN (%)	C:N
1995 Pile	Mean	7.57	2.57	6.12	10.9	0.48	13.1
	%RSD[b]	2.8	4.5	18.6	18.6	12.6	29.8
1996 Pile	s[c]>1/2	7.2	4.13	5.72	10.2	0.46	12.4
Sample 96-D	1/2>s>1/4	7.2	4.02	5.74	10.2	0.42	13.7
	1/4>s>1/8	7.2	3.84	5.13	9.13	0.55	9.33
	1/8>s	7.2	4.37	5.16	9.18	0.65	7.94
	WM[d]	7.2	4.20	5.40	9.61	0.55	10.2
Feedstock	Straw	8.2	NA	50.9	90.6	0.53	96.0
materials	KW[e]	6.2	NA	49.7	88.5	1.82	27.3
	Grass-A	7.3	NA	36.4	64.8	3.96	9.2

Sample Description		NH$_4$-N	NO$_x$-N	PO$_4$-P	K	SO$_4$-S	Ca	Mg	Na
					Plant available (mg kg^{-1})				
1995 Pile	Mean	NA[a]	260.8	407.7	1971.3	140.7	NA	NA	NA
	%RSD[b]		5.4	9.7	5.3	7.3			
1996 PIle	s[c]>1/2	5.8	291	548	2860	207	100	76.3	76.5
Sample 96-D	1/2>s>1/4	5.4	263	565	2680	202	87	67.6	66.6
	1/4>s>1/8	5.3	313	548	2830	231	105	78.4	77.6
	1/8>s	7.1	301	714	3180	225	108	83.2	81.2
	WM[d]	6.3	293	630	2978	217	102.1	78.3	77.1
Feedstock	Straw	NA	NA	NA	NA	NA	NA	NA	NA
materials	KW[e]	NA	NA	NA	NA	NA	NA	NA	NA
	Grass-A	NA	NA	NA	NA	NA	NA	NA	NA

Notes: [a] NA = not analyzed; [b] RSD = relative standard deviation; [c] s = particle size (inches); [d] WM = weighted mean value, which was calculated using equation 1 and the data in Table 6; [e] KW = kitchen waste.

Discussion of the Physical & Chemical Properties

While no literature could be found that specifically characterized compost produced at a golf course, Michel *et al.* (1996) studied a compost produced from a feedstock of a 4:3:1 volumetric ratio of leaf, grass, and brush. The CLGC compost was within their reported ranges for various physical-chemical parameters, except for the content of moisture, carbon, nitrogen, available Ca, and bulk density.

Michel *et al.* (1996) reported a total organic carbon content of 23 to 25% and a TN content of 1.6 to 2.0%, both being about four times higher than what was found in the CLGC compost. Michel *et al.* (1996) reported a feedstock total organic carbon content of 69.5%, suggesting a significant organic matter decrease due to mineralization. Mineralization alone, however, could not account for the low value found in the CLGC compost. Nelson (1996) suggested that composts produced on soil surfaces tend to accumulate soil within the compost, leading to a lower organic matter content. The results of Lisk *et al.* (1992) highlight the variability of organic matter content in yard waste. Studying the characteristics of yard waste compost produced at seven different sites, they found the organic matter to range from 11.6 to 73.8%.

Upon further analysis it became apparent that a large fraction of the CLGC compost was inorganic sand size particles. A wet sieve analysis of the sand size particles

(particle sizes between 0.2 and 2 mm) found that, after ashing, 67.6% of this material remained, suggesting a high sand content. Microscopic observation also confirmed a large sand component.

The high sand content observation resulted in a change to the topdressing mix used at the golf course. The compost was to be blended with sand (30:70 compost:sand mix) before use. The high sand content already in the compost meant the addition of sand was not necessary. Not having to add the sand, may, at first thought, seem like a good thing, however, high quality compost for turfgrass use is becoming more popular because of its ability to suppress disease. Nelson (1996) reported that, all other things being equal, the higher the organic matter, the higher the microbial community health and the greater the disease suppression properties of a compost. This suggests that efforts should be made to minimize the amount of inorganic matter added to the compost during mixing and storage.

Michel *et al.* (1996) reported available Ca values ranging from 579 to 767 mg kg^{-1}. These values were considerably higher than those found in the CLGC compost. Total Ca values found by Michel *et al.* (1996) ranged from 37,000 to 61,000 mg kg^{-1}, which is similar to the range found in the CLGC compost, 49,200 to 81,600 mg kg^{-1}.

The moisture content (MC) reported by Michel *et al.* (1996) ranged from 43.2 to 51.8%, while that of the 1996 CLGC compost ranged from 27.8 to 32.8% (Tables 6 to 8). The CLGC compost was too dry. While the low MC made it easy to handle, it may have a negative impact on the quality of the compost. Hoitink *et al.* (1997) reported that dry composts (< 34% moisture content) became colonized by fungi and are conducive to Phythium diseases. They suggested a MC of at least 40 to 50%.

The *in situ* bulk density (BD) values are presented in Table 8. The mean wet BD value using the large container methodology was 1,042 kg m^{-3} (RSD = 2.12%; four replicates). This value was close to the mean of the *in situ* wet BD value of 1,056. An analysis of the *in situ* data found significant differences (t-test; P=0.05) between depths of 0.15 m and 0.8 m, 0.15 m and 1.05 m, and 0.45 m and 1.05 m. This suggests that some compaction is occurring with depth in the pile. The BD of the compost was considerably higher than that reported by Michel *et al.* (1996), who reported a range of 480 to 639 kg m^{-3}. The high BD was attributed to the higher sand content.

Discussion of the Elevated Mercury Levels

The CLGC compost trace element concentrations were well below the CCME guideline values (Table 1) with the exception of mercury (Hg). Some of the samples also exceeded the maximum concentration of 5 mg kg^{-1} set for Hg by the Canadian Fertilizer Act (CCME 1996). The CLGC compost Hg concentrations ranged from 3.16 to 6.1 mg kg^{-1} which is within the range reported by Alloway (1990) for a broad range of materials (Table 1). These values, however, are very high when compared to those from other yard waste composts. Niederer *et al.* (1995) reported a range of 0.1 to 0.5 mg kg^{-1} in composts made from kitchen waste and garden litter. Lisk *et al.* (1992), investigating seven different yard waste composts, reported values of 0.04 to 0.21 mg kg^{-1}. As the CLGF compost is screened before use on the golf course, we were interested in the distribution of the trace elements based on particle size. It was thought that the finer material may contain higher levels of mercury contamination, but no trends of this nature were evident (Table 3).

The compost feedstock material analyses clearly identified the grass clippings as the source of the Hg contamination (Table 4). Uptake of Hg by turfgrass has been well documented. Hogg *et al.* (1978) reported Bromegrass (*Bromus inermis* var. Carlton) Hg

TABLE 3.
Summary total element concentrations of the finished compost

Sample Description		Total element concentration (mg kg^{-1})										
		As	Cd	Cr	Co	Cu	Pb	Hg	Mo	Ni	Se	Zn
1995 Pile	Mean	3.2	0.411	38.1	3.15	12.2	8.2	5.08	1.09	13.59	0.15[a]	51.9
	%RSD[b]	8.3	9.3	10.5	5.0	8.3	14.1	32.8	19.0	23.4		7.9
1996 Pile	Mean	3.2	0.311	20.9	2.43	24.8	6.6	4.29	1.20	8.61	0.78	165.
96-A,B,C	%RSD	6.3	3.3	14.4	9.9	6.6	5.8	8.8	16.0	16.7	22.2	10.1
Sample 96-D	s[c]>1/2	2.6	0.302	28.4	2.55	12.8	5.9	3.82	0.71	6.63	0.67	46.9
	1/2>s>1/4	2.7	0.348	28.4	2.5	12.6	6.1	3.64	0.79	6.79	0.74	48.1
	1/4>s>1/8	4.2	0.388	34.4	3.61	15.8	7.6	5.84	0.78	8.4	0.67	59.9
	1/8>s	2.9	0.409	38.9	2.71	19.2	7.6	4.54	0.89	6.79	1.06	57.7
	WM[d]	2.9	0.369	34.0	2.72	16.1	6.9	4.34	0.82	6.91	0.87	53.6

Notes: [a]Not detected, value given represents one half the detection limit; [b]RSD = relative standard deviation; [c]s = particle size (inches); [d]WM = weighted mean value, which was calculated using equation 1 and the data in Table 6.

concentrations of up to 2.01 mg kg^{-1} in the plant tissue at soil Hg concentrations of 10 mg kg^{-1} in the top 10 cm of soil. Weaver *et al.* (1984), reporting on the work of others, stated that Hg concentrations were not found to exceed 9 mg kg^{-1} in grass leaves, however, they found a range of 1.4 to 37.6 mg kg^{-1} in the leaves of Bermudagrass (*Cynodon dactylon*) at soil Hg concentrations of up to 50 mg kg^{-1}. Byrtus (1998) found a range of <0.02 to 5.61 mg kg^{-1} in grass clippings taken from golf greens.

The grass mean Hg value of 13.98 mg kg^{-1} is almost twenty times the compost quality guideline value of 0.8 mg kg^{-1}. The grass tissue Hg content found at the CLGC (8.53 to 20.2 mg kg^{-1}) was within the range (1.4 to 37.6 mg kg^{-1}) reported by Weaver *et al.* (1984), but above the maximum value (5.61 mg kg^{-1}) reported by Byrtus (1998). The CLGC grass tissue Hg levels were all above the phytotoxicity threshold of 0.2 to 6.4 mg kg^{-1} reported by Weaver *et al.* (1984). This suggests the possibility that Hg could be limiting turfgrass growth at the CLGC.

The soil data indicate the greens are much more contaminated as compared to the fairway soil. A comparison of the data to the Canadian Soil Quality Guidelines (Table 1) found that arsenic, cadmium, chromium, lead, and mercury all exceed the guideline values for agricultural soils. The Hg value, however, is by far the highest exceedance. The soil Hg concentration ranged from 60.7 to 90.8 mg kg^{-1}, which is nine to fourteen times

TABLE 4.
Summary total element concentrations of the feedstock material and soil

Material	Total element concentration (mg kg^{-1})										
	As	Cd	Cr	Co	Cu	Pb	Hg	Mo	Ni	Se	Zn
Straw	0.5[a]	0.06	0.41	0.035[a]	2.68	0.2	0.005[a]	1.66	0.52	0.2	9.3
KW[b]	3.7	0.095	3.87	0.194	31.8	1.2	0.005[a]	0.29	0.9	1.63	30.1
Grass - Mean	3.4	0.521	33.8	1.438	16.9	9.7	13.98	4.57	5.62	1.48	99.6
Grass - %RSD[c]	22.1	16.9	26.5	32.6	12.3	39.6	42.0	18.0	22.3	51.9	15.6
Green - Mean	31.3	1.63	69.9	5.29	19.6	122	71.9	0.51	15.8	0.25	85.0
Green - %RSD	7.2	9.2	5.0	7.0	13.9	6.2	19.1	10.8	6.8	45.5	6.9
Fairway[d]	4.3	0.38	10.59	5.85	8.66	7.97	0.11	0.29	12.09	0.15[a]	54.07

Notes: [a]Not detected, value given represents one half the detection limit; [b]KW = kitchen waste; [c]RSD = relative standard deviation; [d]Mean of seven samples.

TABLE 5.
Summary total element concentrations for nonguideline elements
in the finished compost and feedstock material

Sample Description		Total element concentration (mg kg^{-1})							
		Al	Ba	Be	Ca	Fe	Li	Mg	Mn
1995 Pile	Mean	3790	75.4	0.194	63067	6870	8.83	20100	500
	%RSD[b]	18.4	0.9	1.1	9.6	3.5	15.5	6.6	3.1
1996 Pile	96-A,B,C - Mean	2073.3	57	0.101	76933	4567	6.19	27067	332
	96-A,B,C - %RSD	13.1	3.5	10.5	6.5	9.3	10.9	4.8	6.4
Sample 96-D	s[c]>1/2	2210	56.8	0.153	63600	5290	5.11	20800	401
	1/2>s>1/4	2580	63.6	0.194	61100	9100	5.34	29500	689
	1/4>s>1/8	3410	73.6	0.231	49200	7750	6.05	19700	449
	1/8>s	2190	64.4	0.168	54700	5300	4	19700	420
	WM[d]	2386	63.3	0.175	57478	6198	4.72	21657	464
Feedstock materials	Straw	84.6	36.7	0.025[a]	1620	107	0.46	709	18.3
	KW	289	10.3	0.025[a]	59800	251	0.81	1770	25.3
	Grass - Mean	1856.7	48.4	0.051	21667	3597	3.48	8247	271
	%RSD	24.6	21.7	87.0	39.4	24.1	15.7	38.7	28.7

Sample Description		Total element concentration (mg kg^{-1})						
		P	Ag	Si	Sr	Ti	Sn	V
1995 Pile	Mean	1640	0.132	322.0	35.2	45.50	0.64	11.67
	%RSD[b]	7.2	22.0	17.0	5.8	51.6	20.5	20.5
1996 PIle	96-A,B,C - Mean	2543	0.05[a]	435	50.7	21.3	0.53	6.01
	96-A,B,C - %RSD	8.1		17.2	6.4	13.8	15.3	11.7
Sample 96-D	s[c]>1/2	2080	0.05[a]	715	36.5	23.7	0.56	7.2
	1/2>s>1/4	2080	0.05[a]	559	31.5	27.6	0.51	8.2
	1/4>s>1/8	2450	0.05[a]	796	31.4	29.7	0.63	9.9
	1/8>s	2500	0.05[a]	731	33.2	20.9	0.78	7.1
	WM[d]	2317		704	33.6	23.7	0.66	7.6
Feedstock materials	Straw	683	0.05[a]	847	3.1	1.3	0.8	0.05
	KW	2240	0.05[a]	283	59.5	17.3	2.03	0.4
	Grass - Mean	4000	0.122	322	33.4	30.9	1.29	6.8
	%RSD	10.6	101.1	30.7	64.3	23.0	26.9	20.0

Notes: [a]Not detected, value given represents one half the detection limit; [b]RSD = relative standard deviation; [c]s = particle size (inches); [d]WM = weighted mean value, which was calculated using equation 1 and the data in Table 6.

the Canadian Soil Quality Guideline of 6.6 mg kg^{-1}. The next highest exceedance was that for arsenic which was approximately three times the guideline value.

The high Hg content in the green was probably a result of the use of a Calo-Clor®, a mercurial fungicide, which was used on the greens up to 1987. This Hg accumulation in the soil has been observed by others. Gilmour and Miller (1973) found the highest Hg accumulations in the thatch layer where the concentrations ranged from 42 to 567 mg kg^{-1}. Mercury accumulation was highest in the top 2.5 cm of the soil of older greens, where the highest concentration was measured at 23.7 mg kg^{-1}. MacLean *et al.* (1973) investigating six greens at three different golf courses in Eastern Canada reported a soil Hg concentration range of 27 to 65 mg kg^{-1} (mean = 53) in the top 5 cm of soil. Byrtus (1998) investigating seven different courses in Alberta, reported a soil Hg

concentration range of < 0.02 to 139 mg kg^{-1}. Most of the Hg was found in the top four cm of the soil. Fushtey (1982) investigating the horizontal and vertical movement of Hg found the majority in the top 5 cm of soil and a significant horizontal movement away from the greens at the surface of the soil. This was attributed to Hg vapor transport. MacLean *et al.* (1973) also suggest run-off and spray drift as potential causes of Hg movement away from the putting greens.

Mercury Material Balance Discussion

To better understand the distribution of Hg within the organic materials at the golf course, several calculations were done. First, the amount of compost available for topdressing and other uses around the golf course were determined. The 1996 compost pile dimensions were length = 4.3 m, width = 3.3 m, and height = 1.2 m. Using equation 1, the pile volume was estimated to be 6.06 m^3. Given that two piles of approximately equal amounts are produced each year, the annual compost production was estimated at 12.12 m^3. Using the mean BD values from Table 8, it was estimated that 12.80 wet tonnes and 8.969 dry tonnes of compost would be produced annually. Only compost passing a 1/4 inch screen is used for putting green topdressing. According to the data presented in Tables 6 and 7, 64.9 to 57.8% of the total dry weight will pass a 1/4 inch screen. Averaging these two results yields a value of 61.4% (RSD=8.2%). Multiplying this by the annual dry compost production, yields a value of 5.507 dry t y^{-1} of fine compost available for topdressing, with the remaining 3.462 dry t y^{-1} available for other horticultural applications. Similar calculations determined that 8.090 wet t y^{-1} of fine and 4.710 wet t y^{-1} of coarse compost would be available.

The Hg concentration in the coarse and fine material was then calculated. The calculated Hg concentrations were 3.74 and 4.77 mg kg^{-1} for the coarse and fine materials, respectively. For topdressing calculations, BD values of the fine material (passing a 1/4

TABLE 6.
Particle size distribution of the 1996 finished compost (sample 96-D). The MC values represent the means of duplicate analyses. All relative standard deviation values were below 6%. Dry weights were calculated using the wet weight and MC values determined for each particle size range. The total wet sample weight was 2.783 kg.

| | Particle Size Range (inches) | | | | |
	s>1/2	1/2>s>1/4	1/4>s>1/8	1/8>s	Totals
MC (%)	23.4	28.7	33.5	33.6	30.4[a]
% wet weight	22.8	16.8	10.7	49.8	100.1[b]
% dry weight	25.1	17.2	10.2	47.6	100.1[b]

Notes: [a]Value calculated from the total wet and total dry weight values. [b]Total percentage d100% due to rounding of data.

TABLE 7.
Particle size distribution of the 1996 finished compost (sample 96-E). The MC values represent the means of triplicate analyses. All relative standard deviation values were below 6%. Dry weights were calculated using the wet weight and MC values determined for each particle size range. The total wet sample weight was 22.0907 kg.

| | Particle Size Range (inches) | | | | | | |
	s>1/2	1/2>s>3/8	3/8>s>1/4	1/4>s>1/8	1/8>s>1/16	1/16>s	Totals
MC (%)	29.4	29.5	30.8	33.7	34.3	31.0	32.0a
% wet weight	15.7	7.1	11.2	11.9	32.3	21.7	99.9b
% dry weight	16.3	7.4	11.4	11.6	31.3	22.0	100.0

Notes: [a]Value calculated from the total wet and total dry weight values; [b]Total percentage d100% due to rounding of data.

TABLE 8.
In situ bulk density properties of the 1996 finished compost pile. Total pile height = 2.1 m. All values based on four replicates.

Depth (m)	MC (%) mean	MC (%) %RSD[a]	Bulk Density (kg m^{-3}) wet mean	Bulk Density (kg m^{-3}) wet %RSD	Bulk Density (kg m^{-3}) dry mean	Bulk Density (kg m^{-3}) dry %RSD
0.15	27.8	4.2	994	1.6	718	1.4
0.45	28.0	5.5	999	4.3	713	3.3
0.8	30.0	3.7	1098	5.2	769	4.5
1.05	32.8	5.1	1132	3.5	761	4.3
mean	29.7		1056		740	
%RSD	7.8		6.6		3.9	

Note: [a]RSD = relative standard deviation.

inch sieve) were also determined using small containers. The mean BD values were 0.7319 wet kg L^{-1} (RSD=3.9%) and 0.5322 dry kg L^{-1} (RSD=4.1%) with a moisture content of 27.3% (RSD=1.3%).

For the material balance calculations, additional data was required, including: the moisture content (MC) of the grass clippings, the kitchen waste (KW), and the straw; the soil BD; and the volume of soil removed in the aeration cores. The mean MC of the grass, KW, and straw were 86.2% (RSD = 2.25%), 76.6% (RSD = 1.2%), and 46.8% (61.3%), respectively. The mean fairway soil dry BD value was 1.303 kg L^{-1} (RSD=3.8%). As the greens were push-up greens (made from local soils), it was assumed the putting green BD would be similar to the fairway soil BD. The number of aeration cores per plot ranged from 235 to 261 cores m^{-2} with a mean value of 247 (RSD=4.6%). The depth of the cores ranged from 6.5 to 9.0 cm, with a mean of 8.0 (RSD=10.1%). Using equation 2, the volume of soil removed during aeration was calculated as 2.5 L m^{-2}. Assuming a core removal efficiency of 90%, the volume of soil removed would be 2.25 L m^{-2} y^{-1}.

A key question at the CLGC and for any golf course where greens have been impacted with pesticide residuals is whether the greens soil should be replaced. To develop a better understanding of the fate of the Hg, a Hg balance on the current operations at the CLGC were completed. A representation of a Hg balance, constructed
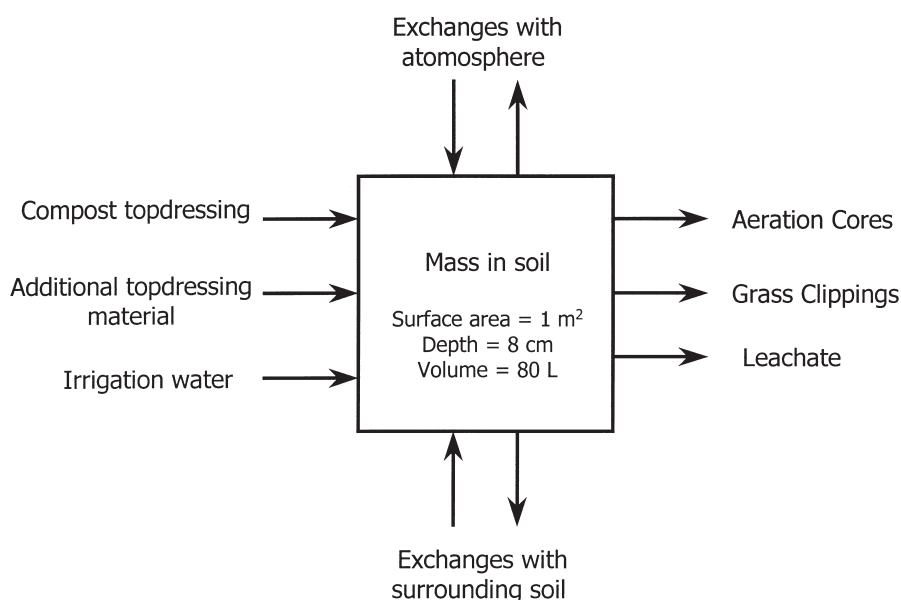

FIgure 1. Mercury material balance for putting green remediation calculations. Calculations were done on a unit area of putting green surface area. Assuming a remediation depth of 8 cm yields a unit area volume of 80 L m^{-2}.

around a unit surface area of putting green, is presented in Figure 1. Mercury inputs include irrigation water, composts used in topdressing, additional topdressing materials, atmospheric deposition, and from the surrounding soil. Mercury outputs would include leachate, the aeration cores, grass clippings, volatilization to the atmosphere, and movement into the surrounding soil. The following discussion summarizes the material balance calculations.

To simplify calculations it was assumed that the amount of Hg added with the irrigation water, the amount of Hg leaching from the soil, and the amount of Hg exchanging with the atmosphere and with the soil outside of the system boundary would be negligible. This seems to be in disagreement with the work of Gilmour and Miller (1973). They reported that after application of Calo-Clor® to yield a soil Hg concentration of 370 mg kg^{-1}, 48% of the Hg was lost to volatilization within 19 days. They concluded, when compared to leaching and grass uptake, volatilization was the dominant form of Hg loss from the soil. Volatilization rates during the 19 day period or beyond the 19 day period were not reported. During Hg application it is expected that some of the Hg will become in direct contact with soil microorganisms or reducing agents, so the rate of volatilization would be greatest immediately after application and would decrease with time. To demonstrate the reduced role of volatilization with time, a simple thought exercise was completed. Assuming a starting concentration of 107.8 mg kg^{-1} and an annual volatilization rate of 48% it was calculated that the soil Hg concentration would be below the CCME soil quality guideline value for Hg (6.6 mg kg^{-1}) within five years. As the CLGC stopped applying Hg fungicides over five years before the soil tests were conducted it is clear that volatilization becomes less significant with time. While the level of volatilization was beyond the scope of this paper it demonstrates how little we do know about the fate of Hg in turf systems.

With the assumptions, the annual rate of remediation would be a function of the mass of Hg removed in the aeration cores, the mass removed in the grass clippings, and the amount added with the topdressing materials. A remediation depth of 8 cm was selected based on the mean depth of the hollow core aeration tines. The mass of Hg in the unit area of soil (mg m^{-2}) at the end of operating year 'n' would be:

$$m_s^n = m_s^{n-1} - m_a^n - m_g^n + m_c^n + m_t^n \quad \cdots\cdots\cdots\cdots (3)$$

where m = the mass of Hg per unit area (mg m^{-2}) in the soil (m_s), aeration cores (m_a), grass clippings (m_g), compost (m_c), and the additional topdressing material (m_t). Assuming the Hg is evenly distributed throughout the unit area, the Hg concentration (mg kg^{-1}) remaining in the soil at the end of any year 'n' would be:

$$c_s^n = \frac{m_s^n}{BD \; V} \quad \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where BD = the dry bulk density of the soil (kg L^{-1}) and V = the volume of soil in the unit area of putting green surface (L m^{-2}).

The starting mass of Hg per unit area of putting green soil to a depth of 8 cm (m_s^0) was calculated to equal 11,240 mg m^{-2} and the concentration in the top 8 cm (c_s^0) was calculated to equal 107.8 mg kg^{-1}. In the first year, the amount of Hg removed with the aeration cores (m_a^1) was estimated to be 316.0 mg m^{-2} y^{-1}, while 8.099 mg m^{-2} y^{-1} would

be removed with the grass clippings (m^1_c). Calculations also found that 2.828 and 0.09158 mg m^{-2} y^{-1} would be added with the CLGC compost (m^1_t) and the additional topdressing material (m^1_t), respectively. Using this data and equations 3 and 4, the mass (m^2_s) and concentration (c^2_s) of Hg in the soil at the beginning of year 2 would be 10,920 mg m^{-2} and 104.8 mg kg^{-1}, respectively.

Calculating the mass of Hg remaining per unit area of putting green surface after the second year of operation becomes more difficult. Unfortunately, from the modeling perspective, all mass transfer values will change with time, except for the Hg content in the additional topdressing material. The mass removed in cores will decrease as the contaminated soil is replaced by the less contaminated top dressing materials. This would be accounted for in the annual decrease in the soil Hg concentration. The amount removed in the grass clippings will also decrease as the soil concentration decreases and presumably the Hg uptake into the tissue decreases. In turn, the decrease in the grass tissue Hg content will result in a decrease in the compost Hg content. To account for these latter two decreases, the mass of Hg in the grass was decreased in proportion to the decrease in the total mass of Hg in the unit area of soil:

$$m_g^{n+1} = m_g^n \, \frac{m_s^{n+1}}{m_s^n} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(5)}$$

Similarly the mass of Hg removed in the compost was decreased as:

$$m_c^{n+1} = m_c^n \, \frac{m_s^{n+1}}{m_s^n} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(6)}$$

Using these equations, the soil Hg concentration at the beginning of year 3 was found to equal 101.8 mg kg^{-1}. These equations were then loaded into a Quattro Pro spreadsheet and the soil concentrations for a 120 year period were calculated. The results are presented in Figure 2. The data fit ($r^2 = 1.0$) an exponential decay model where the soil Hg concentration (c^y_s) at any year (y) is given by:

$$c_s^y = a \, \exp\!\left(-b\,y\right) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(7)}$$

where a and b are constants. The constants were equal to 107.8 mg kg^{-1} and 0.0290 y^{-1}, respectively. Using these values and equation 7, one can calculate the length of time to remediate the greens to the CCME guideline value of c = 6.6 mg kg^{-1}. In the case of the CLGC, the number of years required to remediate the soil was calculated to be 96.3. This is a long period of time!

To put things into perspective, one can compare the annual addition of Hg from the compost to that of a single application of Calo-Clor® applied at the re commended rate. An application of Calo-Clor® would add 438.9 mg Hg m^{-2} y^{-1}. This is over one hundred and fifty times more than the 2.828 mg Hg m^{-2} y^{-1} that would be added with the compost in the first year. Sadly, at the time this paper was submitted (April, 2000) in Canada one could still apply the Calo-Clor®, but would not be able to purchase and apply
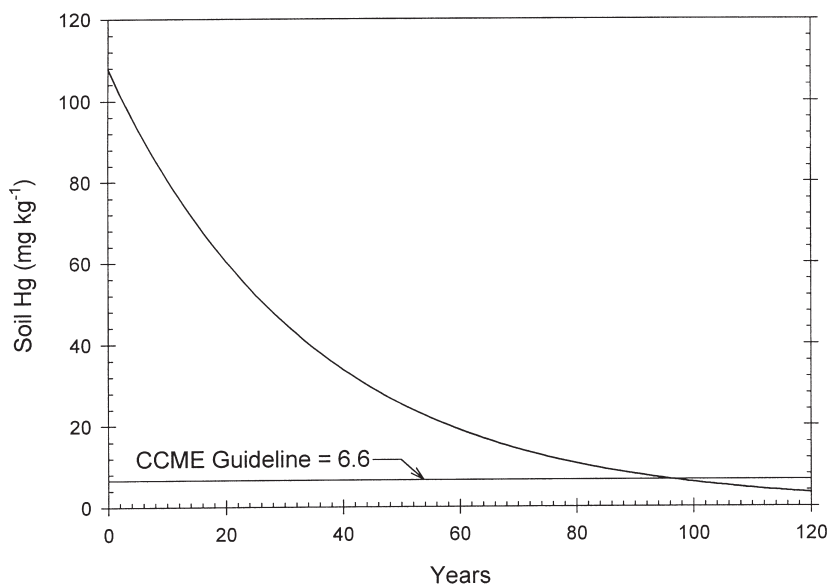
Figure 2. Putting green soil mercury remediation model output over a 120 year period. The model predicted the putting green soil mercury concentration to reach the target value of 6.6 mg kg^{-1} in 96.3 years.

the compost. Furthermore, assuming the single dose of Calo-Clor® was evenly distributed in the top 8 cm of soil, the Calo-Clor® would increase the soil Hg concentration by 4.21 mg kg^{-1}. This equals 64% of the current soil quality guideline level of 6.6 mg kg^{-1}. The good news is that Calo-Clor® cannot be used in Canada beyond the year 2000, so the source of the contamination will be removed and the soils will begin to heal.

As an overall check of the Hg mass balance, the estimated mass of Hg as collected in the grass clippings was compared to the estimated mass of Hg in the compost. Calculations found a total mass of Hg in the grass clipping and the compost to equal 65,520 and 38,480 mg y^{-1}, respectively. Only 58.7 % of the Hg in the grass was recovered in the compost. The unaccounted Hg may be due to errors in estimating collected grass clipping weight, estimating the total compost volume, and from losses to the surrounding environment (air, water, and soil) during composting. The as collected grass clipping estimate has the greatest potential for error, while the losses to the environment are unknown.

Both the fine and coarse compost Hg values are high enough to restrict the use of the compost, e.g., the compost should not be used off-site without the approval of the local environmental authority. The levels, however, are within the risk-based guideline values derived for contaminated materials. The US EPA (1993) defines a clean sludge as having a Hg content of < 17 mg kg^{-1} and Ontario (1996) lists the maximum acceptable value as 11 mg kg^{-1} and a target value of 1.4 mg kg^{-1}. As the fine compost is being returned to the source of the contamination, further soil contamination is not a concern. Furthermore, over the long-term, as the soil Hg concentration decreases, so to will the compost Hg concentration.

The suitability of the coarse compost material for other horticultural uses was investigated. At an application rate of 56 wet t ha^{-1} there was enough coarse compost material to cover 0.0841 ha y^{-1} with a Hg loading rate of 14.68 mg m^{-2} y^{-1}. If mixed to a depth of 15 cm, this application rate results in a soil Hg concentration increase of 0.09789 mg

kg^{-1}. This is only 1.48% of the CCME guideline value of 6.6 mg kg^{-1}. The CCME guidelines also stipulates a maximum cumulative Hg loading equal to 1 kg ha^{-1}. Calculations show that 6.8 applications of the coarse compost would be required before reaching this limit. It is recommended that the coarse material be managed to ensure the maximum cumulative loading is not exceeded for any area. Given the relatively large land area available at the golf course (73.37 ha), this should not be a problem. Coarse compost application records, including the location, date, and application rate, should be kept until the compost Hg concentration is below 0.8 mg kg^{-1}.

Many of the assumptions in the models and the accuracy of the primary data suggest a degree of caution in using the quantitative information provided, however, the exercise does reveal the relative importance of the various materials. Figure 3 was constructed to give a complete picture of Hg flow at the golf course. The system boundary was drawn around the golf course operation. All data was normalized to grams of Hg in a one year period using the data from the first year of the remediation calculations. As shown in Figure 3, 104.4 kg of Hg have accumulated in the putting green soil and 39.22 g would be stored in the composting operation. By far the greatest Hg flow is in the mercurial fungicide. A relative ranking of the various Hg flows finds: mercurial fungicide > aeration cores >> grass clippings > fine compost > coarse compost >> additional topdressing >> straw > kitchen waste. The Hg in the latter three materials (additional topdressing, straw, and kitchen waste) is indicative of where the levels would be if the greens had not been impacted by mercurial fungicides. While the quantitative accuracy of some of the data is questionable, the relative ranking is not. The elimination of the mercurial fungicide, the most important step, has already been done. Now it is important to remove the aeration cores from the system. In normal operations the aeration cores may be returned to the greens. This can be done by allowing the cores to dry on the greens and then matting back into the greens, or by adding the cores to the topdressing or compost material. The practice of returning the cores to the greens must be stopped until the Hg concentration in the greens' soil is below the CCME target value of 6.6 mg kg^{-1}. Although the putting green Hg concentrations exceed the CCME guideline value, the removal of the aeration material will eventually lead to remediation of the soil.
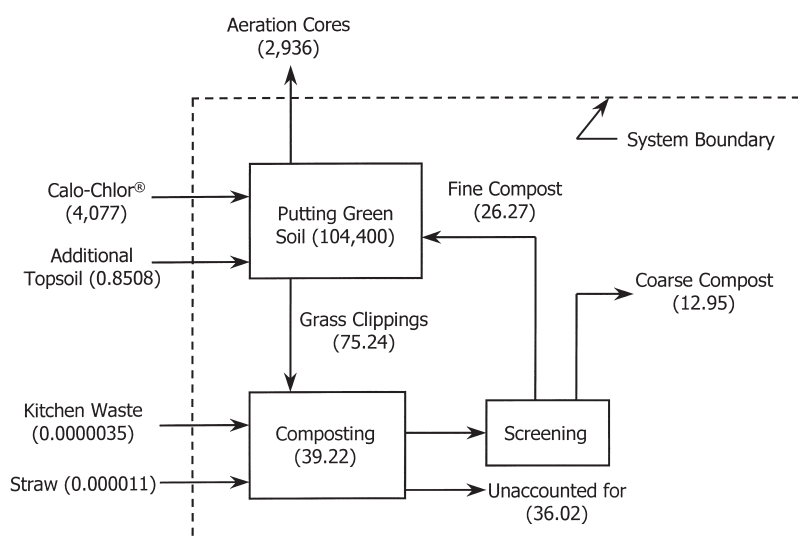

Figure 3. A summary of the mercury mass flow at the Clear Lake Golf Course. All units are in grams of mercury.

The fact that some of the Hg was taken up by the grass suggests a degree of bioavailability, therefore, until a proper scientific risk assessment has been completed by qualified people, care must be taken during the processing and handling of the cores and grass clippings. Considering the work of Gilmour and Miller (1973), who demonstrated a significant volatilization of Hg, the handling of the grass clippings in the clipping storage boxes and the compost system is of particular concern. Furthermore, the Hg in the grass clippings may leach from the compost or be mixed with the surface soils at the composting site. To mitigate this concern, of a composting pad should be constructed. Furthermore, Byrtus (1998) investigated whether Hg contaminated green soil and grass clippings should be classified as a hazardous waste. Using soil and grass samples with Hg concentrations ranging from 0.515 to 90.5 mg kg^{-1} and 4.15 to 5.61 mg kg^{-1}, respectively, the leachable Hg ranged from below detection (<0.0003 mg L^{-1}) to 0.0021 mg L^{-1}, all well below the regulatory limit of 0.2 mg L^{-1} extractable Hg. This suggests that the material may be suitable for landfilling, therefore, a suitable landfill should be found for the ultimate disposal of the cores.

Summary

This paper characterized the on-site compost produced at the Clear Lake Golf Course. The literature did not contain information from other golf courses, so the characteristics were compared to a high grass content yard waste. The compost was found to have a low organic matter content, a low nitrogen content, a high bulk density, and a high sand content. These observations were attributed to the use of a soil composting surface. The moisture content of the compost was also found to be too low due to the strategy used to manage the compost piles.

Historical use of mercurial fungicides has resulted in significant mercury accumulation in the putting greens. The Hg enters the composting system with the grass clippings collected from the greens. The compost contained Hg concentrations ranging from 3.16 to 6.1 mg kg^{-1}, which is four to eight times the Canadian Compost Quality Guideline of 0.8 mg kg^{-1} and much higher than that reported in other yard waste composts. The soil Hg concentration ranged from 60.7 to 90.8 mg kg^{-1}, which is nine to fourteen times the Canadian Soil Quality Guideline of 6.6 mg kg^{-1}. The grass tissue Hg content ranged from 8.53 to 20.2 mg kg^{-1} which were all above a reported phytotoxity threshold.

A simplified model of the current Hg flow in the solid material handled at the golf course was developed. The relative size of the annual Hg flows were: mercurial fungicide > aeration cores >> grass clippings > fine compost > coarse compost >> additional topdressing >> straw > kitchen waste. It was also estimated that 104.4 kg of Hg have accumulated in the top 8 cm of the putting green soil, which covers an area of 9,290 m^2. Calculations suggest that the putting green soil could be remediated to a depth of 8 cm by eliminating the use of mercurial fungicide and by removing the aeration cores from the system. This process would take approximately one hundred years!

The continued use of the compost at the golf course was not identified as a concern. The fine compost used as a topdressing on the greens represents a loading rate of 2.828 mg Hg m^{-2} y^{-1}. This is one hundred and fifty times less than that from a single dose of Calo-Cholr® and is insignificant relative to the high amount of Hg already accumulated in the soil. The amount of Hg in the coarse compost is small relative to the land area available, so it too, will not be a concern. Over the long-term the concentration of Hg in the compost should decline as the putting green soil is remediated.

The Hg in the grass clippings suggests a degree of bioavailability and significant volatilization of Hg has been observed by others (Gilmour and Miller 1973), therefore, the handling of the grass clippings and aeration cores may be of concern. The grass clippings are very wet and reach thermophilic temperatures in the collection boxes and the composting pile. This may result in significant Hg releases to the atmosphere or to the soil underlying the composting area.

Conclusions

Based on this investigation, the following conclusions were made:

1. A composting pad should be installed. This will isolate the compost from the soil, preventing soil from entering the compost and Hg from entering the soil.

2. During curing, pile moisture monitoring and management must be used to ensure the moisture content is kept above 40%.

3. Beginning immediately, the aeration core material should not be returned to the greens. The cores should be disposed of in an appropriate landfill facility.

4. Long-term monitoring of mercury remediation should be implemented. Every five to ten years the compost and aeration cores should be tested for Hg content to track the rate of remediation. This should be continued until the material reach the respective guideline values.

5. Compost application records, including the location, date, and application rate, must be kept for both the fine and coarse compost material until the compost Hg concentration is below the guideline value.

6. As the Hg will be in the system for a very long time, there is the potential for long-term exposure to golf course staff. A health risk assessment must be done with regard to the handling and processing of the aeration cores and grass clippings.

Acknowledgements

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