Weed Seed Viability in Composted Beef Cattle Feedlot Manure

Francis J. Larney* and Robert E. Blackshaw

ABSTRACT

Manure composting has gained increased acceptance by the beef cattle (Bos taurus) feedlot industry in southern Alberta, Canada. Unlike fresh manure, compost is often promoted as being “weed-free.” Studies were conducted with five weed species in 1997 and thirteen in 1999 to examine the effect of feedlot manure composting on weed seed viability. Weed seeds were buried in open-air compost windrows and recovered at various times during the thermophilic phase of composting. Windrow temperature and water contents were also measured. Germinability was zero for all composted weed seeds at all sampling times in 1997. However, some seeds remained viable (positive tetrazolium test denoting respiration) on Day 70. In 1999, only one of the thirteen species retained germinability on Day 21 and only two species had respiring seeds on Day 42. Time–viability relationships during composting were defined by exponential decay models. Lethal temperatures to eliminate viability was species-dependent. In 1999, four weed species were killed in the initial 7 d of composting at a lethal temperature of 39°C while temperatures of >60°C were required for two species. Regression analysis on weed seed viability versus windrow temperature resulted in significant R² values, which showed that only 17 to 29% of the variation in viability was accounted for by temperature. The lack of definitive relationships between temperature and weed seed viability demonstrated that factors other than temperature may play a role in eliminating weed seeds during composting.

In southern Alberta’s beef feedlot industry, feed grain is sourced locally as well as from the neighboring provinces of Saskatchewan and Manitoba. More recently, feed corn (Zea mays L.) has been imported from the U.S. Midwest. Since many weed species retain their viability after digestion by animals (Blackshaw and Rode, 1991), new weeds may be introduced, or an increase in the population of existing weeds may occur, when feedlot manure is land-applied. Manure from unknown feed sources may pose a greater risk of disseminating weeds than manure from feed grown on one’s own operation. There is speculation that introduction of the noxious weed velvetleaf (Abutilon theophrasti Medik.) to New York farms in the 1970s was as a result of spreading manure from animals fed corn imported from the U.S. Midwest (Mt. Pleasant and Schlather, 1994). Cudney et al. (1992) germinated weed seeds present in manure from five dairies in California and found viable numbers of up to 19,730 seeds Mg⁻¹, depending on collection site. They recognized that this was only a fraction of the total number, due to dormancy. A survey of manure from 26 New York farms revealed an average of 75,100 weed seeds Mg⁻¹ manure (Mt. Pleasant and Schlather, 1994). At a typical local annual application rate of 45 Mg ha⁻¹, approximately 340 seeds m⁻² would be added to the soil seed bank.

For these reasons, some farmers in southern Alberta are reluctant to use fresh manure from nearby feedlots as a source of plant nutrients, especially for specialty crops such as potato (Solanum tuberosum L.), sugar beet (Beta vulgaris L.), and timothy hay (Phleum pratense L.). Farmers choosing to use fresh feedlot manure may concentrate its application on already weedy fields or on fields where they can practice intensive weed control, if they suspect the manure contains large amounts of weed seeds. This potentially lowers the available land base for the large volumes of manure produced in the region, leading to overapplication and its associated effect on soil, water, and air quality (Chang and Ezt, 1996; Chang et al., 1998).

Composting is a biological process, whereby regular introduction of air by mechanical turning stimulates aerobic microorganisms to reduce organic materials such as livestock manure to a more stable material similar to humus (Rynk, 1992). Increasingly, composting is being adopted by the beef feedlot industry in southern Alberta as an alternative handling method to traditional direct haulage of fresh manure from feedlot to field (Larney et al., 2000).

Agricultural compost is often promoted as “weed-free” since one of the benefits of composting is the destruction of weed seed viability by the high temperatures (>60°C) achieved during the process (Eghball and Lesoin, 2000; Tompkins et al., 1998; Wiese et al., 1998). However, Cudney et al. (1992) found that composted manure (6–8 wk old) from five California dairies contained varying amounts of viable weed seeds. Churchill et al. (1996) suggested that increased turning frequency during composting reduced survival of all weed species, probably as a result of increased temperatures. Grundy et al. (1998) believed that weed seeds that survived the composting process did so as a result of localized “cool spots” caused by inefficient turning of the windrow. Viable weed seeds may also contaminate finished compost in open-air windrows via dissemination and deposition by wind.

Early workers (Atkeson et al., 1934; Harmon and Keim, 1934; Stoker et al., 1934) buried weed seeds in static piles of cattle, horse (Equus caballus), and chicken (Gallus gallus domesticus) manure and found that reduction in viability varied by weed species. Hopkins (1936) reported that there was a critical temperature below which moderate periods of heating had little effect on viability and above which germination fell off rapidly. In more recent research with composting, Wiese

Abbreviations: CDD, cumulative degree days.
et al. (1998) found that field bindweed (\textit{Convolvulus arvensis} L.) was the most difficult of six weed species to eliminate. The five other weed species were killed if compost temperatures were maintained at 72°C for 3 d. Eghball and Lesoing (2000) reported that when composting manure is kept moist, weed seed viability may be destroyed even though the critical temperature is not reached, possibly because of compost phytotoxins. Ligneanu and Watt (1995), Marchiol et al. (1999), and Ozores-Hampton et al. (1999) also showed that the toxic components of leachates from compost or soil–compost mixtures reduced germination of certain weeds, grasses, and legumes.

This study examined weed seed viability of common weed seeds found in southern Alberta during beef feedlot manure composting. It sought to elucidate relationships between duration of composting and lethal temperatures required to eliminate weed seed viability.

**MATERIALS AND METHODS**

**Compost Windrows**

The study was performed at the Agriculture and Agri-Food Canada Research Centre, Lethbridge, Alberta during the summers of 1997 and 1999. Cattle manure, where barley (\textit{Hordeum vulgare} L.) straw had been used for bedding, was removed from feedlot pens with a front-end loader. In 1997, the manure was loaded onto a manure spreader and then deposited into windrows. The mechanical action of the manure spreader ensured some initial mixing on Day 0 (20 May 1997). In 1999, the manure was loaded into a truck and deposited into compost windrows on 20 July 1999 (Day 0) with little or no mixing. The windrows were turned seven times over a 99-d period in 1997 and a 70-d period in 1999 (Table 1) with a tractor-pulled EarthSaver windrow turner (Fuel Harvesters Equipment, Midland, TX). This represented the active thermophilic composting phase, and as such produced an almost mature compost. After 100 d the compost entered a mesophilic or “curing” phase (no turning) for a further 90 d until windrow temperature approached ambient.

The windrows were on an east–west orientation and varied in length from 13 to 15.2 m. They were about 1.6 m high and 3.6 m wide at the base. The 1997 study was conducted outdoors and hence exposed to precipitation. The 1999 study was conducted in a roofed composting facility with no walls, so that compost was exposed to ambient air temperatures but not precipitation.

**Weed Seed Placement**

**1997 Study**

In 1997, treatments consisted of (i) weed species, (ii) time of removal from the compost windrow, and (iii) location within the compost windrow in a factorial design. Two grass [green foxtail (\textit{Setaria viridis} (L.) Beauv.) and wild oat (\textit{Avena fatua} L.)] and three broadleaf weed species [redroot pigweed (\textit{Amaranthus retroflexus} L.), stinkweed (\textit{Thlaspi arvense} L.), and wild buckwheat (\textit{Polygonum convolvulus} L.)] were selected.

A total of 300 sample bags (6.5 × 5.5 cm), each containing 200 seeds, was prepared for the study. The bags were made from nylon screening with a mesh size of 500 µm and an open area of 49%. This was fine enough to retain the seeds while allowing their exposure to temperature and moisture conditions within the windrow. Of the 300 bags, 225 (five weed species × five removal times × nine windrow locations) were buried in the compost windrow and 75 were used as control samples (five weed species × five sampling times × three replicates). The nine windrow locations were: east–top, east–middle, east–bottom, center–top, center–middle, center–bottom, west–top, west–middle, and west–bottom. The east, center, and west locations corresponded to approximately 25, 50, and 75% of the length of the windrow, while the top, middle, and bottom locations were centered on the windrow at approximately 0.9, 0.6, and 0.3 m from the ground.

To facilitate weed seed recovery from the compost, the five bags of each species were tied together with orange-colored twine that ran to the outer surface of the windrow, where it was labeled with the species name.

The control sample bags were placed in a covered plastic pail, which had holes to allow air entry but not moisture. The pail was attached to a pole at a 2-m height near the windrow. Three control bags were removed at each sampling date for comparison with the composted samples.

At each of the five weed seed removal times (Table 1), all bags were recovered from the compost windrow just before turning. One bag from each of the nine locations was sampled and stored at 0.5°C, while the remaining bags were reburied in the compost immediately after turning.

**1999 Study**

In 1999, the experimental design was modified to include more weed species (13), only one replicate of the three windrow locations (top, middle, and bottom), and only one control sample per weed species. The thirteen weed species included the five used in 1997 and eight new ones: downy brome (\textit{Bromus tectorum} L.), false cleavers (\textit{Galium aparine} L.), foxtail barley (\textit{Hordeum jubatum} L.), green smartweed \textit{Polygonum} \textit{scautum} Moench), round-leaved mallow (\textit{Malva pusilla} Sm.), stork's-bill \textit{Erodium cicutarium} (L.) L’Her. ex Ait.], scentless chamomile \textit{Matricaria perforata} Merat), and wild mustard \textit{Sinapis arvensis} L.).

A total of 208 nylon-mesh bags was prepared (16 bags per weed species, each with 200 seeds) as described previously. Of the 208 bags, 195 (13 weed species × 5 removal times × 3 windrow locations) were buried in the compost (in the center of the windrow, 50% along its length) and 13 were used as controls. The control samples were placed as described for 1997 and removed at the last sampling date (Day 91).

Weed seeds were removed from compost at five times over the composting period (Table 1), the same number as in 1997. However, the first removal time was earlier (Day 7 vs. Day 14) and the last removal time later (Day 91 vs. Day 70) than in 1997.

**Compost Temperature**

Windrow temperatures were monitored with thermocouples and a data logger (Sciemetric, Nepean, ON, Canada). Thermocouples were installed as soon as the windrows were formed. They were removed just before turning and reinstalled.
as soon as possible after turning was completed. In 1997, temperatures were measured adjacent to weed seed bags at six (east–top, east–middle, east–bottom, center–top, center–middle, center–bottom) of the nine locations. In 1999, temperatures were measured at the top, middle, and bottom locations at the east and west ends of the windrow (approximately 25 and 75% along its length). The average of these two temperature values was used to estimate the temperature that corresponded to the location of the weed seed bags (50% along the windrow length). In both studies, temperatures were logged every 20 min and then averaged to give daily mean values.

The degree day concept was used to integrate temperatures over the composting period. Using a base temperature of 40°C, degree days were calculated for each location on each day as:

\[ \text{degree day} = (\text{mean daily temperature} - 40) \]

If the mean daily temperature was <40°C, then degree days were 0. The degree day values were then summed to give cumulative degree days (CDD) for each location on each sampling date. Guidelines for the control of pathogens during composting refer to the material maintaining a temperature of >55°C for at least 15 days during the composting period (Canadian Council of Ministers of the Environment, 1995). Also, during the high-temperature period, the windrow should be turned at least five times. We decided to use a 40°C base temperature as we believed that weed seed viability may be affected at temperatures of <55°C.

Compost Water Content

In conjunction with turning, and hence weed seed removal dates, compost samples (approximately 0.6 kg) were taken for water content determination from two vertical windrow faces exposed with a small front-end loader. In 1997, the water content sample was a composite from five locations on the exposed faces. In 1999, samples were taken at the top, middle, and bottom locations of each vertical face (three locations × two replicates). Water content was expressed on a wet weight basis after oven-drying at 60°C to a constant weight.

Weed Seed Viability

Weed seed viability was determined as outlined by Blackshaw and Rode (1991). Briefly, all 200 seeds from each of composted and control weed seed bags were placed on moistened filter paper in Petri dishes in a controlled environment chamber (temperature 20°C, relative humidity 40–50%) and allowed to germinate. Seeds that did not germinate were subjected to a tetrazolium test (Grabe, 1970) by placing them in Petri dishes on filter paper moistened with a solution of 1% tetrazolium. After 48 h at room temperature, the seeds were examined for red staining at the growing point, an indication of respiration and hence viability. Seeds with a positive tetrazolium test were summed with germinable seeds to give viable seeds. Viable seeds were then expressed as a percent of total seeds to arrive at a percent viability. In some cases, viability was also expressed as a percent of the control sample (control = 100% viability) to account for the variation in the viability of the control samples among weed species and between the same species in the two studies.

Statistical Analysis

The effect of vertical location on weed seed viability in 1997 and on cumulative degree days in 1997 and 1999 was analyzed with the general linear models procedure (SAS Institute, 1989). Regression analysis was used to define relationships between time and viability, and temperature and viability.

RESULTS

Weather Conditions

Total precipitation during the active composting phase from 20 May–29 July 1997 was 212 mm, which may be considered as a water input to the compost windrow. The 1999 windrow was under a roofed structure, which prevented any water addition via precipitation. Mean monthly air temperatures were 11.3, 16.0, and 18.2°C for May–July 1997 and 16.4, 18.8, 12.9, and 8.4°C for July–October 1999.

Compost Temperature

Mean daily compost temperatures showed a rapid rise in the early days of composting in 1997, with the maximum temperature for the entire composting period occurring on Day 2 for the middle (63.3°C) and bottom (68.6°C) locations (Fig. 1a). The top location was much cooler than the middle and bottom locations throughout the composting period and reached a maximum temperature of 55.5°C on Day 81 by which time the last weed seed removal date had passed (Day 70). The influence of turning on compost temperatures was denoted by the
sudden drop in temperature as cooler air was introduced to the windrow, followed by a rapid rise as aerobic microbial activity was stimulated (Fig. 1a).

In contrast, the mean daily temperatures in the 1999 study were much cooler in the early part of the composting period (Fig. 1b) because manure was formed into windrows on Day 0 and left untended until Day 7. The absence of a premixing on Day 0 precluded a rapid early rise in temperature. Subsequently, temperatures climbed steadily reaching maxima of 46.8°C (Day 29) for the top location, 67.1°C (Day 47) for the middle location, and 67.9°C (Day 49) for the bottom location.

In 1997, the bottom location had significantly more cumulative degree days (CDD) than the middle location, which in turn had significantly more than the top location on Days 14, 21, 29, and 50 (Fig. 2a). By Day 70, the bottom (941 CDD) and middle (878 CDD) locations were not significantly different from each other, as the middle location showed a larger increase in temperature following the turning event on Day 50 (Fig. 1a). However, the top location was still significantly cooler (494 CDD).

In 1999, there were no significant differences in CDD with location on Days 7 and 14 (Fig. 2b). On Day 7, there were 0 CDD at the top, 13 CDD at the middle, and 1 CDD at the bottom location. The middle and bottom locations were not significantly different from each other on any of the five weed seed removal dates. The top location was significantly cooler than the middle and bottom locations on Days 21, 42, and 91. The CDD values at the top location ranged from 12.2% of the middle location on Day 21 to only 6.5% of the middle location on Day 91. The cooler temperatures associated with the top location are due to the semicircular shape of the windrow, which exposed the top location to more ambient conditions.

In the 1997 study, it took 29 d for the bottom location to attain 573 CDD. The cooler temperature regime of the 1999 study is demonstrated by a similar number of CDD (559) over a longer period (42 d).

**Compost Water Content**

Average water content of the compost windrow was 0.71 kg kg$^{-1}$ at the start of the 1997 study on Day 0 (Fig. 3a). Optimal water contents for composting range from 0.40 to 0.65 kg kg$^{-1}$ (Rynk, 1992). Moisture content decreased to 0.65 kg kg$^{-1}$ on Day 29 and 0.51 kg kg$^{-1}$ on Day 70. A total of 212 mm of precipitation fell on the windrow during the 70-d composting period, which helped prevent excessive water loss.

In the 1999 study, water content was lower at all points in the composting process than in 1997 (Fig. 3a). This was due to roofed protection of the windrow from incoming precipitation. Water content averaged 0.67 kg kg$^{-1}$ on Day 0 and decreased to 0.52 kg kg$^{-1}$ on Day 42 (close to the value on Day 70 for the 1997 study). By Day 91, compost water content had dropped to 0.29 kg kg$^{-1}$. Larney et al. (2000) reported water mass losses of up to 75% during the thermophilic phase of summer composting due to high evaporation rates.
In the early stages of composting in 1999, all vertical locations behaved similarly (Fig. 3b). By Day 21, however, the top location was substantially drier (0.45 kg kg⁻¹) than the middle (0.59 kg kg⁻¹) and bottom (0.65 kg kg⁻¹). This was due to the semicircular shape of the windrow as the top location was more exposed to evaporative drying.

### Time–Viability Relationships

#### 1997 Study

In 1997, viability of the control samples (average of five sampling dates) was 32% for wild buckwheat, 86% for green foxtail, 76% for redroot pigweed, and 75% for wild oat. Because of a poor lot of stinkweed seed, the viability of the control samples was very low (average of 4.2%). Germinability was zero for all composted weed seeds at all sampling times, showing that composting had a dramatic effect on weed seed survival. However, even though weed seeds did not germinate when subjected to composting, some remained viable as denoted by a positive tetrazolium test. Since there were zero germinable seeds in composted samples, all viability values for compost in Table 2 were entirely due to seeds with a positive tetrazolium test. Green foxtail, redroot pigweed, and wild oat survival in compost was quite similar. By Day 14, the viability of these species had dropped to between 2 and 12% compared with 64 to 89% for the control samples. By Day 29, their viability was 0.2 to 6% while at Day 70 viability was zero for all three species. Since the viability of control samples for stinkweed was so low, comparisons with composted samples are not that meaningful.

Wild buckwheat seed was more resilient to composting. On Day 14, viability was similar to the control samples (Table 2). Even on Day 29, viability of the composted samples was not significantly different from the control. By Day 50, however, viability of wild buckwheat had dropped to <2% at all locations in the windrow compared with 34% for the control sample. By Day 70, viable seeds remained in the top (1.8%) and bottom locations (0.2%), which may be enough to cause a weed infestation if the compost was land-applied at this stage.

There were 25 comparisons (five weed species × five sampling dates) of weed seed location in the compost windrow on viability in the 1997 study. However, there was only one comparison that showed a significant location effect. This was wild buckwheat on Day 21, when the seeds placed near the top of the windrow showed significantly lower viability (4.3%) than those placed at the middle (13.8%) and bottom (13.3%) locations (Table 2). A possible explanation for this might be higher concentrations of oxygen at the top of the windrow than at the middle and bottom locations, which may have encouraged germination of wild buckwheat seeds into lethal conditions, hence reducing overall viability of the recovered seeds.

#### 1999 Study

In 1999, viability of the control samples ranged from 13.5% for stinkweed to 95.5% for downy brome (Table 3). Viability of four weed species (downy brome, scentless chamomile, stork’s-bill, and wild mustard) had dropped to zero after just 7 d of composting. Of the remaining nine species on Day 7, germinable seed and respiring seed (positive tetrazolium test) contributed to viability of five species (false cleavers, green smartweed, redroot pigweed, round-leaved mallow, wild buckwheat) while the viability of four species was due to respiring seed only (foxtail barley, green foxtail, stinkweed, wild oat).

By Day 14, viability of foxtail barley had dropped to zero. Of the eight species with viable seeds on Day 14, round-leaved mallow was the only one to retain germinability. The 14% viability was comprised of 10.7% germinable seed and 3.3% respiring seed. The viability of the other seven species was entirely due to

### Table 2. Effect of location and time of removal from compost windrow on weed seed viability in 1997.

<table>
<thead>
<tr>
<th>Weed</th>
<th>Location</th>
<th>Day 14</th>
<th>Day 21</th>
<th>Day 29</th>
<th>Day 50</th>
<th>Day 70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green foxtail</td>
<td>control</td>
<td>87.7a †</td>
<td>85.1a</td>
<td>88.7a</td>
<td>84.1a</td>
<td>82.3a</td>
</tr>
<tr>
<td></td>
<td>compost, top</td>
<td>2.7b</td>
<td>0.0b</td>
<td>0.0b</td>
<td>0.0b</td>
<td>0.0b</td>
</tr>
<tr>
<td></td>
<td>compost, middle</td>
<td>6.8b</td>
<td>0.0b</td>
<td>0.0b</td>
<td>0.0b</td>
<td>0.0b</td>
</tr>
<tr>
<td></td>
<td>compost, bottom</td>
<td>9.2b</td>
<td>1.2b</td>
<td>2.3b</td>
<td>0.7b</td>
<td>0.0b</td>
</tr>
<tr>
<td>Redroot pigweed</td>
<td>control</td>
<td>72.9a</td>
<td>78.3a</td>
<td>73.8a</td>
<td>77.6a</td>
<td>77.1a</td>
</tr>
<tr>
<td></td>
<td>compost, top</td>
<td>3.5b</td>
<td>0.7b</td>
<td>0.0b</td>
<td>0.0b</td>
<td>0.0b</td>
</tr>
<tr>
<td></td>
<td>compost, middle</td>
<td>3.8b</td>
<td>5.7b</td>
<td>0.2b</td>
<td>0.0b</td>
<td>0.0b</td>
</tr>
<tr>
<td></td>
<td>compost, bottom</td>
<td>7.1b</td>
<td>5.3b</td>
<td>1.0b</td>
<td>0.0b</td>
<td>0.0b</td>
</tr>
<tr>
<td>Stinkweed</td>
<td>control</td>
<td>3.4a</td>
<td>2.8a</td>
<td>2.0a</td>
<td>5.1a</td>
<td>7.7a</td>
</tr>
<tr>
<td></td>
<td>compost, top</td>
<td>0.5b</td>
<td>0.3a</td>
<td>1.2a</td>
<td>1.0b</td>
<td>4.3a</td>
</tr>
<tr>
<td></td>
<td>compost, middle</td>
<td>0.0b</td>
<td>0.2a</td>
<td>4.3a</td>
<td>1.2b</td>
<td>6.8a</td>
</tr>
<tr>
<td></td>
<td>compost, bottom</td>
<td>0.0b</td>
<td>0.3a</td>
<td>4.3a</td>
<td>0.0b</td>
<td>1.7a</td>
</tr>
<tr>
<td>Wild buckwheat</td>
<td>control</td>
<td>26.5a</td>
<td>36.3a</td>
<td>33.0a</td>
<td>33.7a</td>
<td>31.9a</td>
</tr>
<tr>
<td></td>
<td>compost, top</td>
<td>32.7a</td>
<td>4.3c</td>
<td>6.4a</td>
<td>1.7b</td>
<td>1.8b</td>
</tr>
<tr>
<td></td>
<td>compost, middle</td>
<td>32.4a</td>
<td>13.8b</td>
<td>13.0a</td>
<td>0.7b</td>
<td>0.0b</td>
</tr>
<tr>
<td></td>
<td>compost, bottom</td>
<td>12.0a</td>
<td>13.3b</td>
<td>17.0a</td>
<td>1.0b</td>
<td>0.2b</td>
</tr>
<tr>
<td>Wild oat</td>
<td>control</td>
<td>79.5a</td>
<td>64.4a</td>
<td>66.6a</td>
<td>85.4a</td>
<td>77.1a</td>
</tr>
<tr>
<td></td>
<td>compost, top</td>
<td>12.0b</td>
<td>2.7b</td>
<td>0.0b</td>
<td>0.0b</td>
<td>0.0b</td>
</tr>
<tr>
<td></td>
<td>compost, middle</td>
<td>5.6b</td>
<td>1.0b</td>
<td>0.0b</td>
<td>0.0b</td>
<td>0.0b</td>
</tr>
<tr>
<td></td>
<td>compost, bottom</td>
<td>2.0b</td>
<td>0.3b</td>
<td>1.3b</td>
<td>0.0b</td>
<td>0.0b</td>
</tr>
</tbody>
</table>

† Within columns and weed species, means followed by a different letter are significantly different (P < 0.05).
Table 3. Effect of time of removal from compost windrow on weed seed viability in 1999.

<table>
<thead>
<tr>
<th>Weed</th>
<th>Control</th>
<th>Day 7</th>
<th>Day 14</th>
<th>Day 21</th>
<th>Day 42</th>
<th>Day 91</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downy brome</td>
<td>95.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>False cleavers</td>
<td>54.0</td>
<td>2.5†</td>
<td>6.5‡</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Foxtail barley</td>
<td>79.0</td>
<td>0.5‡</td>
<td>1.0‡</td>
<td>1.2‡</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Green foxtail</td>
<td>91.0</td>
<td>2.8‡</td>
<td>12.0‡</td>
<td>9.0‡</td>
<td>3.3‡</td>
<td>0.0</td>
</tr>
<tr>
<td>Green smartweed</td>
<td>62.5</td>
<td>21.0‡</td>
<td>7.2‡</td>
<td>6.5†</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Redroot pigweed</td>
<td>77.5</td>
<td>15.7‡</td>
<td>30.7‡</td>
<td>15.2‡</td>
<td>3.0‡</td>
<td>0.0</td>
</tr>
<tr>
<td>Round-leaved mallow</td>
<td>21.0</td>
<td>13.5‡</td>
<td>14.0†</td>
<td>6.5†</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Scentless chamomile</td>
<td>94.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Stinkweed</td>
<td>13.5</td>
<td>5.5‡</td>
<td>8.5‡</td>
<td>3.3‡</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Stork's-bill</td>
<td>94.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Wild buckwheat</td>
<td>52.0</td>
<td>14.7‡</td>
<td>30.7‡</td>
<td>15.2‡</td>
<td>3.0‡</td>
<td>0.0</td>
</tr>
<tr>
<td>Wild mustard</td>
<td>50.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Wild oat</td>
<td>66.0</td>
<td>0.7‡</td>
<td>0.8‡</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

† Germinable seed and respiring seed contributing to viability.
‡ Zero germinable seed, respiring seed only contributing to viability.

Regression Analysis

The time–viability relationships during composting may be described with an exponential decay model of the form:

\[ y = a \exp(-bx) \]

where \( y \) = weed seed viability and \( x \) = days of composting. Equations were fit to the four weed species common to both studies (green foxtail, redroot pigweed, wild buckwheat, and wild oat). The control sample viability values were used for \( x = 0 \). Stinkweed was omitted because of its low level of viability in the control sample in 1997. All four species (Fig. 5) had highly significant exponential decay relationships in both studies (\( P < 0.001 \)) except for wild buckwheat in 1999 (\( P = 0.08 \)). These relationships were also significant for the remaining species in the 1999 study: false cleavers (\( P = 0.04 \)), foxtail barley (\( P < 0.001 \)), green smartweed (\( P = 0.001 \)), and stinkweed (\( P = 0.04 \)) (data not shown). Obviously, relationships could not be fitted for the four weed species in 1999, where viability had dropped to zero by Day 7 (downy brome, scentless chamomile, stork’s-bill, and wild mustard).

Temperature–Viability Relationships

Lethal Temperatures

Using daily mean temperature values and viability data, lethal temperatures were estimated as the mini-
Fig. 6. Relationship between cumulative degree days (CDD) and viability of wild buckwheat seed in 1997 and 1999. Viability expressed as percent of control samples.

The lethal temperature for wild oat was 53.8°C. This compares with the 48°C reported by Thompson et al. (1997) to prevent over 90% germination of wild oat in a heated soil. Thompson et al. (1997) believed that the maximum temperature required to prevent germination was of greater importance than the duration of heating.

If high windrow temperatures were associated with the elimination of weed seed viability, then we would expect to observe location effects on viability since location had a highly significant effect on windrow temperature, especially in 1997. However, this was not the case. In fact, the only significant effect of location on viability in 1997 (wild buckwheat on Day 21, Table 2) could not be explained by temperature differences. The top location, which had significantly lower viability (4.3%) than the middle and bottom locations (13.3–13.8%) was significantly cooler (161 CDD) than the middle (347 CDD) and bottom locations (466 CDD).

Regression Analysis

Regression analysis on weed seed viability versus windrow temperature (expressed as CDD) was conducted on all five weed species in 1997 and on nine of the thirteen species in 1999. The four weeds (downy brome, scentless chamomile, stork’s-bill, and wild mustard) where viability had reached zero after just 7 d of composting in 1999 were excluded. The only significant linear regressions were for wild buckwheat in 1997 and 1999 (Fig. 6) and wild oat in 1997 (data not shown). The relationships showed that weed seed viability decreased as CDD increased. However, there was a large amount of scatter in the data and $R^2$ values showed that only 17% (wild oat, 1997), 20% (wild buckwheat, 1997), and 29% (wild buckwheat, 1999) of the variation in viability was accounted for by CDD. This demonstrates that factors other than temperature (e.g., germination into lethal conditions or pathogen infestation) may affect weed seed viability during composting. Ammonia toxicity to viable weed seeds is another possible mecha-
nism as high concentrations of ammonia are present in the early stages of manure composting (Rynk, 1992).

### Initial 14 Days of Composting

Since most of the effects on viability occurred in the first 14 d of the composting process, the temperature and water content conditions during that period were examined in more detail.

Weed seed viability may be affected more by a combination of high temperatures and wet conditions rather than high temperatures alone. Bloemhard et al. (1992) suggested that dry seeds are more resistant to heat while Thompson et al. (1997) indicated that heat treatment of weed seeds may have more severe effects on fully imbibed seed. Egley (1990) found that species tolerance to heat and moisture varied. Some weed seeds, heated to 70°C in dry soil (0.02 kg kg⁻¹), were killed after 7 d. Some heated in moist soil (0.19 kg kg⁻¹) survived for up to 3 d at 70°C, or up to 7 d at 60°C, while others were killed after 3 d at 50°C. Some weed species have “hard seed,” which prevents germination and protects against decay. The combination of moisture and heat may render hard seed permeable to water. Horowitz and Taylorson (1984) found that soaking velvetleaf seed for 1 h at 70°C reduced the number of hard seeds from 99 to 15%.

In 1997, average temperatures and water contents in the 0- to 14-d period of composting were higher than in 1999 (Table 4). Overall, average temperature was 14.6°C higher in 1997 (54.6 vs. 40.0°C) and the maximum temperature attained was 13.3°C warmer in 1997 (62.3 vs. 49.0°C) and average water content was slightly wetter (0.71 versus 0.65 kg kg⁻¹). To compare overall viability between the two studies, the total viable seeds were summed for all five species in 1997 and all 13 species in 1999. This value was then expressed as a percentage of the total number of seeds buried in the compost. In 1997, 8.8% of all composted weed seeds remained viable after 14 d, while in 1999, overall viability was lower (6.2%), despite the 1999 study having lower temperatures and slightly drier conditions.

Temperature and water content conditions for the 0- to 7-d period in 1999 offer further insight into interactions between temperature, water content, and weed species in our study. Further experiments concentrating on this lower temperature range may be required under both moist and dry compost conditions, with and without turning. Our compost water contents did not vary enough in the early stages of composting to fully test the effect of water content on viability. All water contents were in the wet range (0.60–0.70 kg kg⁻¹). It may be worthwhile to examine the behavior of weed seeds in drier conditions since manure is often dry (<0.40 kg kg⁻¹) at pen cleaning in southern Alberta. However, microbial activity and hence temperature is suppressed if the substrate is too dry (Rynk, 1992) and water is generally added to ensure optimum composting. We did not examine the effect of compost leachates on weed seed germination. Production of water-soluble organic phytotoxins such as short-chain fatty acids (e.g., acetic acid), during composting has been reported (Kirch-
mann and Widen, 1994). Shiralipour et al. (1997) found an inhibitory effect of acetic acid on the germination of cucumber (*Cucumis sativus* L.). Ozores-Hampton et al. (1999) found that germination of ivyleaf morning glory (*Ipomoea hederacea* L.), barnyard grass (*Echinochloa crus-galli* L.), and common purslane (*Portulaca oleracea* L.) was delayed and decreased by extracts from 3-d-, 4-wk-, and 8-wk-old composts as compared with a mature compost extract (1 yr old). This was attributed to higher amounts of acetic acid in the immature composts.

The lack of viable weed seeds makes compost an attractive soil amendment, especially in organic farming where weed control with herbicides is not an option. However, our study demonstrated that care should be taken to ensure that the composting process is complete, with adequate turning, as some weed seeds remained viable even after 70 d of composting (wild buckwheat, 1997).

The question is often posed as to whether application of compost rather than fresh manure will lead to lower herbicide inputs to cropping systems since introduction of viable weed seeds is potentially lower. The size of the soil seedbank and the annual input from weeds already present in the field will determine the relative advantage of compost. If soil seedbank numbers are low and manure seed counts are high, then composting may alleviate a potential weed problem. However, if soil seedbank numbers are high and manure seed counts are low, then composting may not affect weed populations. Mt. Pleasant and Slatin (1994) believed that when exotic weeds are present in manure, which may occur if feed is sourced from a different ecozone, manure application may introduce these exotics to the soil seed bank. Few seeds are required to develop into a major infestation, perhaps necessitating the use of a new herbicide and increasing herbicide inputs. In this scenario composting may be beneficial.

**CONCLUSIONS**

Our study showed that while composting dramatically reduced weed seed viability, the exact mechanism was unclear. Temperature required to achieve complete elimination of viability was species-dependent, as was the duration of exposure to those temperatures. The lack of definitive relationships between compost temperature and weed seed viability suggests that other mechanisms, such as phytotoxic leachates, may play an important role in the destruction of viability.

**ACKNOWLEDGMENTS**

The authors thank the Alberta Agricultural Research Institute (Farming For the Future Matching Grants Program, Project no. 97M-179) for partial financial support of this study. The technical help of Greg Semach, Andrew Olson, and Paul DeMaere is gratefully appreciated.

**REFERENCES**


