Probability estimation of silage effluent from horizontal silos

P. SAVOIE

Agriculture and Agri-Food Canada, Sainte-Foy Research Station, Département de génie rural, Université Laval, Sainte-Foy, QC, Canada G1K 7P4. *Received 30 June 1993; accepted 15 October 1994. Contribution No. 504.*

Savoie, P. 1995. **Probability estimation of silage effluent from horizontal silos.** Can. Agric. Eng. **37**:049-056. A mathematical model was developed to predict daily flow and total accumulated silage effluent from a mechanically compacted horizontal silo (bunker or clamp). Generated daily rainfall over a 50-year period was used to estimate effluent flow and year-to-year variations from a 200 t dry matter (DM) grass crop (1250 t silage at 16% DM) harvested by three different systems. A direct-cut non-stop system (DCNS) resulted in a total of 1600 L of effluent or less per t DM in a wet climate (1440 mm rain per year) and 1120 L/t DM or less in a dry climate (720 mm rain per year) at 95% probability (19 years out of 20). Daily maximum flows at 95% probability were 185 L/t DM per day in the wet climate and 119 L/t DM per day in the dry climate. A design effluent storage capacity of 3 m^3 per 100 t silage was found adequate for one-day storage but could result in effluent overflow after two days under very wet conditions. A second harvest system of direct-cut restricted to non rainy days only (DCNR) reduced total effluent to 1150 L/t DM in the wet climate and 670 L/t DM in the dry climate. Daily maximum flows at 95% probability were 109 L/t DM per day in the wet climate and 54 L/t DM per day in the dry climate, a reduction of 41 to 55% compared to DCNS. A third harvest system that included field wilting (WS) during 6 h resulted in total effluent of 68 L/t DM in the wet climate and 36 L/t DM in the dry climate. Daily maximum flows at 95% probability were 3 L/t DM per day in the wet climate and 2 L/t DM per day in the dry climate. Moderate wilting almost eliminated the problem of silage effluent but it delayed the harvest period from 5 days with the DCNS system to up to 18 days with the WS system.

Un modèle mathématique a permis de prédire l'écoulement quotidien et annuel de jus d'ensilage, ou effluent, des silos horizontaux. On a estimé l'effluent d'une masse de 200 t de matière sèche (t MS) de graminées récoltées selon trois systèmes différents et simulés pendant 50 années de données climatiques quotidiennes. Un système de coupe directe sans arrêt (CDSA) a produit 1600 L d'effluent ou moins par t MS avec une probabilité de 95% (19 années sur 20) dans un climat humide (1440 mm de pluie par année) et 1120 L/t MS ou moins dans un climat plus sec (720 mm de pluie par année). Le débit maximal quotidien, à 95% de probabilité, était de 185 L/t MS par jour dans le climat humide et 119 L/t MS par jour dans le climat sec. Une citerne de captage aux dimensions de 3 m^3 par 100 t d'ensilage serait adéquate pour l'entreposage des écoulements d'une journée mais déborderait après deux jours dans des conditions extrêmement humides. Un deuxième système de récolte de coupe directe limité aux jours sans pluie (CDSP) a réduit le volume annuel d'effluent à 1150 L/t MS dans le climat humide et à 670 L/t MS dans le climat sec. Les débits maximaux quotidiens à 95% de probabilité étaient de 109 L/t MS par jour et de 54 L/t MS par jour respectivement, soit 41 à 55% moindres que pour le système CDSA. Un système de récolte avec 6 heures de préfanage (RP) a réduit considérablement le volume d'eau dans l'ensilage ainsi que l'écoulement de jus; l'effluent annuel n'était que de 68 L/t MS dans le climat humide et de 36 L/t MS dans le climat sec. Les débits maximaux quotidiens étaient de 3 et 2 L/t MS par jour respectivement. Le préfanage a pratiquement éliminé le problème des effluents d'ensilage. Cependant la période de récolte est passée de 5 jours avec le système CDSA à 18 jours avec le système RP.

INTRODUCTION

Silage effluent is produced as a result of excess moisture and pressure in storage. The quantity of effluent flow depends mainly on the crop moisture content but also on the type of silo, the chop length, the use of additives, and the weather during harvest. Silage effluent is undesirable on at least two counts. First, effluent contains soluble nutrients and can represent as much as 10% dry matter loss (McDonald et al. 1991). Secondly, it has a very high biological oxygen demand (BOD), in the order of 40,000 to 90,000 mg 0_2/L (McDonald et al. 1991). This makes it one of the most concentrated farm pollutants; it can rapidly deplete fresh water oxygen and kill aquatic life when the effluent is directed to streams.

Considering the problem of effluent, why would farmers be tempted to harvest wet silage? One advantage with a short wilting period is faster harvest and removal of crop from the field. The crop is less likely to be damaged by rain or prolonged respiration. Another advantage is the suggested increase in milk production both per animal and per hectare from direct cut crops conserved with formic acid compared to crops subjected to prolonged wilting, especially in a very humid climate (Gordon 1981). These advantages explain at least in part why farmers have reduced the average wilting period in very humid regions such as the United Kingdom (Offer et al. 1991; Haigh 1993). However, a shorter wilting period results in higher crop moisture and produces more silage effluent. The number of pollution incidents in England and Wales due to silage effluent increased from 250 in 1979 to over 1000 in 1987 (Beard et al. 1989).

Many farmers are not adequately equipped to collect and store silage effluent in short wilting or direct cut systems. Even specifically designed effluent collection systems are not immune to pollution incidents. Drainage channels might be blocked by grass; the collection tank might be too small for over-filled silos, very wet silages or rain water falling over the storage area. In either case, effluent will overflow and can pollute watercourses. Unusually wet seasons may also cause pollution incidents in areas not usually concerned with silage effluent. Graves and Vanderstappen (1993) mentioned increased awareness of silage effluent pollution in Pennsylvania.

Legislation in several countries now requires complete containment of silage effluent. Disposal is done either by controlled spreading on the land or by feeding to animals. Farmers must build storage reservoirs that will contain the silage effluent. Current recommendations are in the order of 3 m^3 per 100 t of silage (ADAS 1984). However, variable rainfall and crop moisture can influence the actual effluent flow.

Numerous studies have been concerned with silage effluent. McDonald et al. (1991) and Woolford (1984) provided useful syntheses. McDonald et al. (1991) described three empirical equations to predict the volume or mass of effluent produced. In clamp silos, practically no effluent flowed when the dry matter was above 30%. In tower silos, the dry matter had to be higher than 30% to avoid effluent flow when the silo height was greater than 12 m. The most important factor explaining the quantity of effluent flow was dry matter content.

The empirical equations cited previously predicted total effluent only. They did not predict the time course of effluent flow. Pitt and Parlange (1987) presented a time related effluent flow equation and applied it to tower silos.

The objective of the present paper was to propose a time related effluent flow equation and apply it to horizontal silos. This study also considered the effect of rainfall probability on total and daily effluent flow.

METHODOLOGY

Theoretical model

Silage effluent flow is generally characterized by three steps: initial cell breakdown and slow effluent flow, rapid release of cell water and increased effluent flow, and finally a tapering off period. This pattern of flow can be modelled by the an equation suggested by Pitt and Parlange (1987):

$$\frac{dM}{dt} = -\alpha\,(M - M_\infty)\,(1 - e^{-t/\beta}) \qquad (1)$$

where:

M = moisture content, dry basis (kg water/kg dry matter),

t = time (d),

α = effluent flow rate coefficient (d^{-1}),

M_∞ = equilibrium moisture content after all effluent has flowed out of the silo (kg/kg), and

β = cell breakdown parameter (d).

If cell breakdown is very rapid, β is very small and Eq. 1 reduces to a rate equation dependent on (M-M_∞). Assuming that all cell water is not immediately available to flow as effluent, Eq. 1 is appropriate. Considering the boundary condition of initial moisture in the silo, M_o, at $t = 0$, the solution to Eq. 1 is:

$$M = M_\infty + (M_o - M_\infty)\ \exp\,[\alpha\,\beta\,(1 - e^{-t/\beta}) - \alpha\,t] \qquad (2)$$

Given an initial moisture content, M_o, the flow pattern of effluent will depend on parameters α, β, and M_∞. These parameters must be estimated from experimental data. Pitt and Parlange (1987) suggested that M_∞ in tower silos could be related to pressure exerted on the silage. In horizontal silos, there are at least two experimental constraints that make it difficult to relate M_∞ to pressure. First, there is a wide variation in moisture within the silo such that an average final moisture M_∞ is difficult to measure experimentally. Secondly, horizontal silos are usually compacted with wheeled or tracked tractors; pressure is non-uniform and difficult to measure. Meanwhile, it is relatively easy to measure total effluent flow from a horizontal silo by collection in a drainage system.

By mass balance, it is possible to use initial moisture M_o (kg/kg) and total effluent flow W (kg effluent/kg silage) to calculate an average final equilibrium moisture M_∞. Some dry matter (DM) is carried in the effluent; its concentration is expressed by d_j (kg DM/kg effluent). The concentration of water in the effluent is w_j (kg water/kg effluent). The sum of d_j and w_j is 1. By mass balance:

$$M_\infty = \frac{M_o - W\,w_j\,(M_o + 1)}{1 - W\,d_j\,(M_o + 1)} \qquad (3)$$

The actual effluent flow may also be calculated by transforming Eq. 3;

$$W = \frac{M_o - M_\infty}{(M_o + 1)\,(w_j - M_\infty\,d_j)} \qquad (4)$$

Pitt and Parlange (1987) suggested that, because effluent dry matter was small, it could be neglected when calculating total effluent (i.e. $d_j = 0$ and $w_j = 1$). In very wet silage, this assumption will cause considerable error in effluent estimate. For example, a silage at $M_o = 5.25$ (84% on a wet basis) and $M_\infty = 4.55$ will produce 0.112 kg effluent/kg silage if one assumes $w_j = 1$. However, typical silage effluent contains 95% water and 5% dry matter (McDonald et al. 1991). Assuming $w_j = 0.95$ and $d_j = 0.05$, total effluent produced is 0.155 kg effluent/kg silage, a 38% difference.

Given appropriate values of M_o, β, and M_∞ or W, one can estimate actual moisture M at any time with Eq. 2. The corresponding effluent flow is calculated with Eq. 4 by replacing M_∞ by the value of M.

Parameter estimation

The parameters needed to estimate silage effluent flow are total expected volume, effluent dry matter and values for β and α in Eq. 2. These parameters are estimated from experimental data taken from the literature.

The total volume of effluent depends on the type of silo and several other factors. From observations taken from grass clamp silos over 16 years at 2 sites, Bastiman and Altman (1985) derived the empirical equation:

$$V = 767 - 5.34\,D + 0.00936\,D^2 \qquad (5)$$

where:

V = total volume of effluent (L/t of silage), and

D = silage dry matter (g DM/kg silage).

Equation 5 predicts total effluent as a function of fresh forage dry matter only. The original data (Bastiman 1976) showed a wide variation from each side of the curve. There are several other factors that might affect the quantity of effluent: additives, the fineness of chopping, wheel pressure applied when filling the silo, the drainage system within the silo. Recent studies have shown that acid additives and fineness of chopping increase early flow rate but not the overall total quantity (O'Kiely 1990).

The mass of effluent, W (kg/t), is equal to the volume of effluent, V (L/t), multiplied by density, ρ (kg/L). The density of silage effluent depends on the dry matter content of the effluent. Woolford (1984) quoted effluent dry matters ranging between 10 and 100 g/kg, with an average of 60 g/kg. McDonald et al. (1991) presented silage effluent composition from nine farm silos; dry matter ranged between 6 and 84 g/kg, with 40 g/kg as average. O'Kiely (1990) measured a range of dry matters between 20 and 100 g/kg, with 50 g/kg as average. Therefore, an average effluent dry matter of 50 g/kg was assumed, i.e. $d_j = 0.050$ and $w_j = 0.950$. Since water has a density of 1 kg/L and forage particles have a density of 1.5 kg/L (Pitt 1983), the weighted density of effluent is 1.025 kg/L. The mass of effluent is:

$$W = V\rho \tag{6}$$

This value can be used in Eq. 3 to find the equilibrium moisture.

Parameter β used in Eqs. 1 and 2 determines how quickly cell sap is released; it is closely related to the time of peak effluent flow. Various sources show that peak effluent flow is delayed as dry matter increases. Bastiman (1976) indicated peak flows 2, 5, and 3 days after ensiling for dry matters of 16, 18, and 22% respectively. Bridgestocke (1989) observed peak flow 7 days after ensiling at 18% DM. Jones et al. (1990) observed peak flow on the second day with forage at 16% DM. A simple equation is suggested to relate β to dry matter:

$$\beta = 1 + \left(\frac{D-120}{30}\right) \tag{7}$$

Equation 7 shows that, for a low dry matter of 120 g/kg, the value of β is 1. The value of β increases linearly up to a value of $\beta = 7$ when D is 300 g/kg. As will be seen later, this corresponds approximately to a shift in peak flow from the first or second day for very wet forage (12% DM) to the seventh day when the forage dry matter approaches 30%.

The last parameter required to estimate the flow rate is α. It corresponds to the rate at which effluent flows out of the silo. A convenient way to estimate as α is to define another parameter, t_{90}, the time (d) for 90% of the volume to flow out of the silo. McDonald et al. (1991) indicated that, at 16% DM, 90% of effluent had flowed out after 20 days. O'Kiely (1990) presented data indicating faster effluent release when formic acid was used. He also observed faster effluent release with a short chop length. A simple equation to calculate the time for 90% of effluent flow is:

$$t_{90} = 10 + \left(\frac{D-120}{10}\right) + f_c + f_a \tag{8}$$

where:

f_c = chopping factor, and

f_a = silage additive factor.

For very wet material (D = 120 g/kg), 90% of effluent is released in 10 days if the chop factor is 0 (for chop length less than 50 mm) and the additive factor is 0 (when formic acid is used). In a dry material (D = 300 g/kg) without acid (f_a = 5 days) and with coarse chopping (f_c = 5 days), 90% of effluent would be released after 38 days.

Once t_{90} is estimated, parameter α can be calculated from Eq. 2. Table I shows typical values of parameters needed to predict silage effluent flow.

Variations of crop dry matter

Forage dry matter is the single most important factor influencing the amount of silage effluent. When DM is above 30%, no effluent is expected from horizontal silos. The initial DM of forage is known to increase with maturity. The change has been found to be almost linear on a dry matter basis for alfalfa (0.05 kg water reduction/kg dry matter per day; Savoie and Marcoux 1985) and for timothy (0.08 kg/kg per day; Savoie et al. 1984). A model presented by McGechan (1990) and adapted to United Kingdom conditions showed that initial dry matter of ryegrass ranged between 16% at heading and 38% ten weeks later. On a dry basis, this corresponded to a reduction of about 0.05 kg water/kg dry matter per day). A simple linear model for ryegrass expresses this relationship:

$$M_o = 5.25 - 0.05\,(t_c - t_h) \tag{9}$$

where:

t_c = calendar or Julian day when the crop is actually cut (d), and

t_h = Julian day at which grass harvest begins, typically at an initial moisture of 5.25 kg/kg (84% on a wet basis). A dry matter of 16% (M_o = 5.25) is usually the physiological limit of forage to hold cell water. However, instances of crops as

Table I. Typical parameters to estimate silage effluent flow (assuming short chop length and use of acid additive)

Dry matter (g/kg)	Volume of effluent (L/t)	M_o (kg/kg)	M_∞ (kg/kg)	Time for 90% flow (d)	β (d)	α (d^{-1})
140	203	6.143	5.112	12	1.67	0.2161
160	152	5.250	4.545	14	2.33	0.1934
180	109	4.556	4.093	16	3.00	0.1747
200	73.4	4.000	3.713	18	3.67	0.1592
220	45.2	3.545	3.381	20	4.33	0.1460
240	24.5	3.167	3.083	22	5.00	0.1347
260	11.3	2.846	2.810	24	5.67	0.1249
280	5.6	2.571	2.555	26	6.33	0.1164

wet as 14% DM or lower have been observed (McDonald et al. 1991). A dry matter content below 16% in the standing crop is largely explained by the presence of surface moisture due to rain or dew.

Surface moisture due to rain will also occur on the wilting crop in the field and on the crop being transported to the silo. McGechan (1990) proposed a model in which rain absorption was a function of rainfall intensity. Since rainfall intensity is not often available, a simpler model based on total daily rainfall was proposed. It assumed that 25% of daily rain was retained on the crop and that the typical crop cover was 500 g DM/m^2. When 1 mm of rain fell over 1 m^2, 250 g of water were assumed to be absorbed by 500 g of DM. The surface water absorption model was therefore:

$$M_s = 0.5\, r \qquad (10)$$

where:

M_s = surface moisture on the crop (kg of water/kg of DM), and

r = daily rainfall (mm).

When rainfall occurred, the total crop moisture was the sum of M_o plus M_s where $M_s \leq 2.08$ kg/kg. The maximum M_s retained on the crop's surface was based on the difference between 12% DM expressed as moisture on a dry basis, $M = 7.33$, and 16% DM, $M = 5.25$. The model also assumed that 25% of M_s remained on the crop on the day after rain.

Field wilting is an important method by which crop moisture can be reduced. In this study, most simulations considered harvest without wilting, i.e. moisture in the silo was $M_o + M_s$. However, when wilting occurred on a non-rainy day, it was assumed that 1.5 kg water/kg DM evaporated during the day. This water evaporation rate is typical of a fresh grass crop in an undisturbed windrow in a moderately dry climate (Savoie et al. 1984).

Simulation of silage effluent flow

Equations 1 to 8 were used to simulate effluent flow for fixed values of DM. A first group of simulation runs was done to illustrate the effluent pattern for various DM values, the effect of chop length and additives, and the effect of harvest capacity (between slow and fast). Results included the amount of silage effluent which would flow out daily from a horizontal silo. Equations 9 and 10 were incorporated into a more extended model to consider the effect of maturity and rainfall. In this case, initial crop dry matter was influenced by date of harvest and by previous rainfall pattern. Two contrasting climates were compared. A dry climate was assumed to have 0.3 probability of rain on any day and a total yearly rainfall of 720 mm. A wet climate had 0.6 daily probability of rain and 1440 mm rainfall per year. A random number generator was used to determine if the day was rainy or not. If the day was rainy, a second random number was generated to estimate the amount. The daily amount of rainfall was assumed to be distributed as a logarithmic function from an exponential distribution (Law and Kelton 1982): there was a 63% chance of receiving less than the average amount and an 86% chance of receiving less than twice the average. The average daily rainfall (r_d, mm) was based on total annual precipitation (r_y, mm) and the daily rainfall probability (p_r, fraction):

$$r_d = \frac{r_y}{365\, p_r} \qquad (11)$$

The actual daily rainfall (r, mm) was estimated as a function of a random number F:

$$r = -r_d \ln (F) \qquad (12)$$

where F is a random number generated from a uniform distribution between 0 and 1. This rainfall amount was used to update the amount of surface water on the crop according to Eq. 10. When rain was considered, the typical harvest capacity for direct-cut was 40 t DM per day. With a wilting system, capacity was assumed to decrease to 25 t DM per day because of the need for a delay between mowing and harvest.

RESULTS AND DISCUSSION

Effluent flow from constant levels of forage moisture

Figure 1 illustrates daily effluent flow curves obtained from the model for dry matters in the range of 14 to 24%. Peak flow is reached after 3 days at 14% DM; it is reached on the 6th day at 24% DM. Flow rates are relatively small for dry matters above 24%. At 14% DM, a maximum daily flow of 28 L/t of silage is expected. Under static conditions (considering no variation in initial dry matter), it is wise to plan to collect daily as much as 2.8 m^3 of effluent per 100 t of silage.

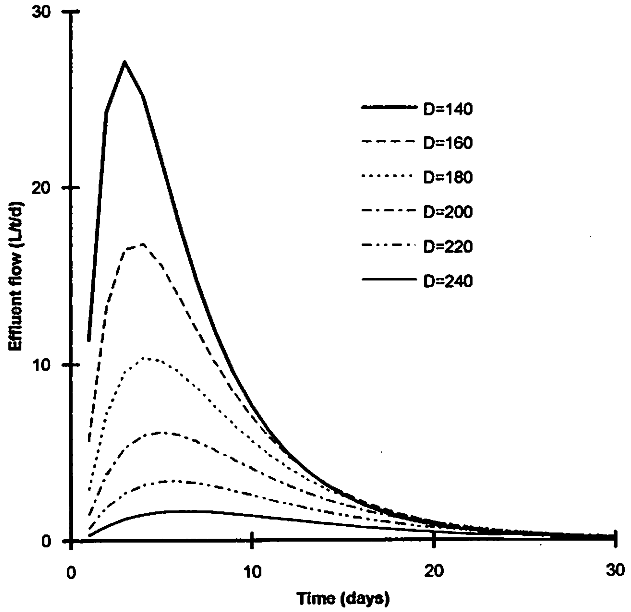

Fig. 1. Daily silage effluent flow over time as a function of forage dry matter D (g DM/kg forage).

The effects of acid additives and chop length are shown in Fig. 2. The model assumed that total effluent quantity was not affected. However, the initial rate of flow was higher with acid and with a short chop length. The effluent flow was prolonged without acid or with a coarser chop length.

When harvesting was done over several days, the effluent from each day's mass of silage was accrued in total flow. Figure 3 illustrates the effect of harvesting the same quantity

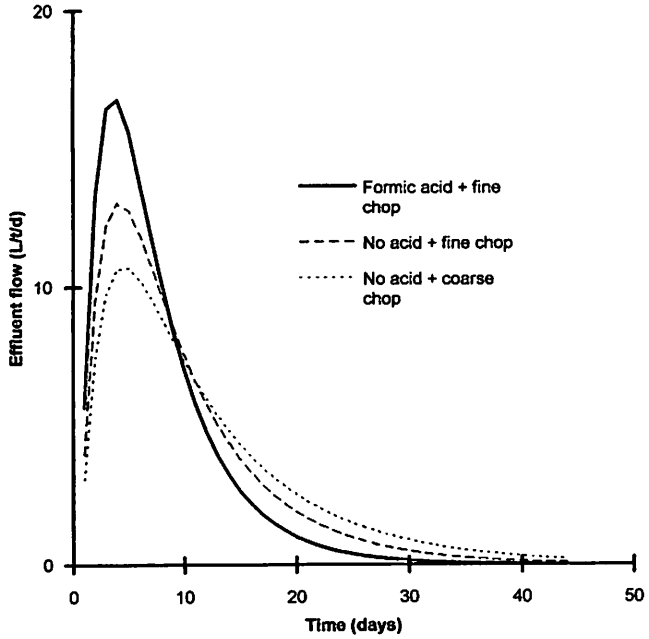

Fig. 2. Effect of formic acid and chop length on effluent flow at a DM of 160 g/kg.

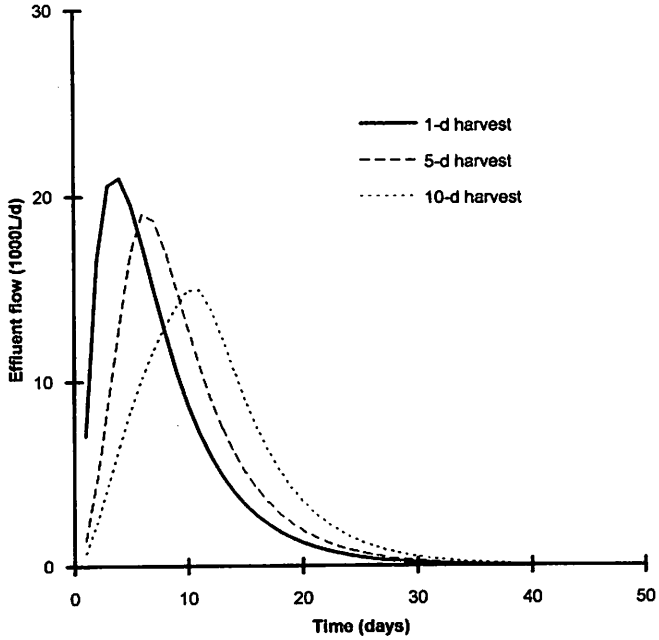

Fig. 3. Effect of harvest capacity on total daily effluent flow for a 200 t DM harvest at a DM of 160 g/kg.

of forage (200 t DM or 1250 t silage at 16% DM) over 1, 5, or 10 days. The slower harvest rate had the advantage of spreading effluent flow over a longer period. The 10-day harvest reduced the peak daily flow by 29%. Under assumptions of constant DM, harvest rate did not change total effluent. Table II shows the maximum effluent accumulations over various periods for the three harvest rates. If effluent containment must be adequate for 2 days of storage, results show a total effluent flow between 30,000 and 43,000 L for 1250 t of silage. This represents between 2.4 and 3.4 m^3 per 100 t silage. With a very high harvest rate, the silage effluent container will either have to be larger or emptied more quickly during the peak flow period. These results were based on constant levels of DM. The next section considers when initial DM varied because of rain and crop maturity.

Effluent flow from variable levels of forage moisture

Simulations were run for 50 years of first cutting by generating random rainfall events as described in the methodology. A total of 200 t DM of forage was harvested at a rate of 40 t DM/d for direct-cut and 25 t DM/d for wilted forage. Direct-cut harvest was either a non-stop system (i.e. harvest every day during 5 consecutive days) or a stop-when-it-rains system (i.e. harvest only on non-rainy days). Harvesting in the wilted silage system always stopped when it rained.

Table II. Maximum effluent accumulation (L) over different periods, assuming a constant dry matter of 16% and a total harvest of 200 t DM (1250 t silage)

Harvest duration	Maximum effluent accumulation (L) over period				
	1 day	2 days	3 days	7 days	Total
1 day	21,500	42,600	62,700	125,700	195,000
5 days	19,500	38,600	56,100	115,600	195,000
10 days	15,300	30,600	44,900	97,000	195,000

The amount of effluent collected varied from one year to the next because of different rainfall patterns and their effect on surface moisture and maturity of the harvested crop. Figure 4 shows how the maximum daily effluent flow varied from year to year between 18,000 and 38,000 L/d, essentially due to differences in surface moisture. The most likely daily f

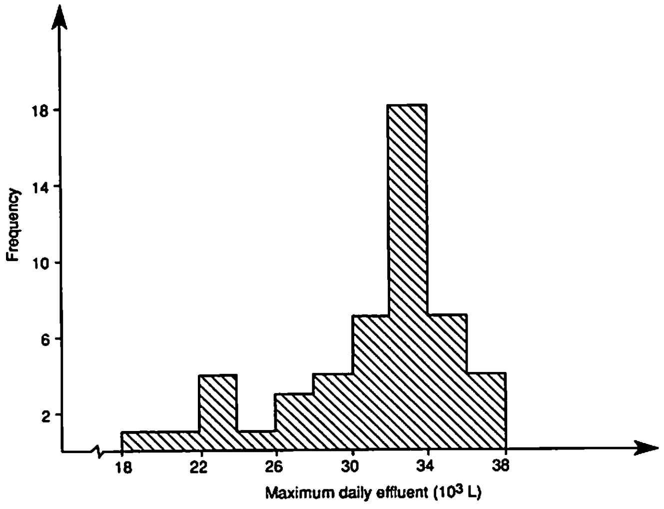

Fig. 4. Histogram of maximum daily silage effluent observed each year during a 50-year simulation for a non-stop, direct-cut 5-day harvest system ensiling 200 t DM initially at 16% DM.

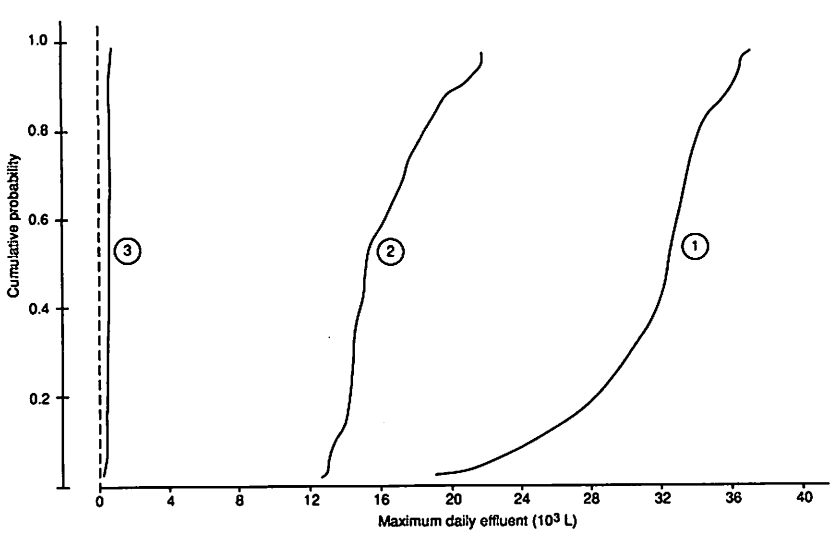

Fig. 5. Probability curves of maximum daily silage effluent with 3 different harvest systems for 200 t DM initially at 16% DM, a 0.6 daily rainfall probability and 1440 mm yearly rainfall. Systems are (1) direct-cut, non-stop; (2) direct-cut, stop when it rains; (3) wilted.

low (at 50% probability) was 32,000 L/d. The information on Fig. 4 was converted into cumulative probability on Fig. 5 (the right side curve).

The maximum daily effluent can readily be identified for any probability level. At 95% probability (19 years out of 20), the maximum daily effluent was 37,000 L/d. Figure 5 also compared effluent production under three different harvest policies. The direct-cut harvest system with interruption on rainy days considerably reduced the maximum daily effluent (15,000 L/d at 50% probability and 21,000 L/d at 95% probability). The wilted system produced almost negligible amounts in comparison to direct-cut; the maximum daily effluent ranged between 300 and 800 L/d. Tables III and IV provide the 50% and 95% probability levels for effluent production over 1, 2, 7, and 50 (total) days. If the effluent storage tank must be designed to hold 2 days of flow at the 95% probability (19 years out of 20), the direct-cut, stop-when-it-rains system would require a capacity of 42,800 t which is equivalent to 3.3 m^3 per 100 t silage. This is 10% more than the conventional recommendation of 3 m^3. The risk of effluent overflow might occur occasionally if the tank is emptied every second day. This risk would be eliminated by emptying the tank every day rather than every second day.

The above results have been obtained for a rainfall probability of 0.6 and an annual rainfall of 1440 mm. It was also assumed that the initial dry matter was 16%. In a drier climate where rainfall probability was assumed to be 0.3 and annual rain 720 mm, the fresh crop was also considered to have a higher initial dry matter of 18%. Figure 6 illustrates the probability curves of maximum daily effluent for the three harvest systems under this drier climate. Table V gives the 95% probability level of accumulated effluent in the drier climate. The wilted system produced hardly any effluent. The direct-cut systems still produced important quantities of effluent.

The number of calendar days required to harvest the full 200 t DM for the 3 harvest systems ranged from 5 days with the direct-cut non-stop system to 18 days with the wilted system in the wet climate (Table VI).

Management alternatives to reduce effluent flow

Clearly the most efficient way to reduce effluent is by wilting. Results in Table IV showed that total effluent from a direct-cut non-stop system (DCNS) was 319,000 L or 1600 L/t DM, at 95% probability, while total effluent from a wilting system (WS) was 13,600 L or 68 L/t DM. In a drier climate (Table V), the total effluent was 224,000 L (1120 L/t DM) for DCNS and 7200 L (36 L/t DM) for WS.

The use of a direct-cut system on non-rainy days only (DCNR) reduced total effluent from 1600 to 1150 L/t DM in a wet climate and from 1120 to 670 L/t DM in a dry climate.

Table III. Median (50% probability) maximum effluent over different accumulation periods for 3 harvest systems ensiling 200 t DM. (Rain prob. 0.6; rainfall = 1440 mm/yr; initial DM = 16%)

Harvest system	Effluent (L) accumulated over period			
	1 day	2 days	7 days	Total
1. Direct-cut non-stop	32,300	63,000	183,100	282,500
2. Direct-cut, stop-when-raining	15,500	30,300	95,700	211,700
3. Wilted	540	1,080	3,600	11,700

Table IV. The 95% probability level of maximum effluent over different accumulation periods for 3 harvest systems ensiling 200 t DM. (Rain prob. = 0.6; rainfall = 1440 mm/yr; initial DM = 16%)

Harvest system	Effluent (L) accumulated over period			
	1 day	2 days	7 days	Total
1. Direct-cut non-stop	36,900	71,900	207,500	319,100
2. Direct-cut stop-when-raining	21,800	42,800	124,200	229,700
3. Wilted	640	1,270	4,250	13,600

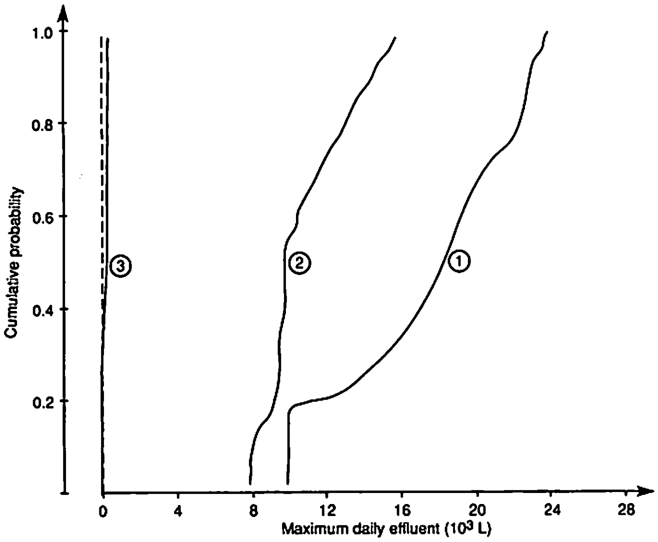

Fig. 6. Probability curves of maximum daily silage effluent with 3 different harvest systems for 200 t DM initially at 18% DM, a 0.3 daily rainfall probability and 720 mm yearly rainfall. Systems are (1) direct-cut, non-stop; (2) direct-cut, stop when it rains; (3) wilted

The "price" of not harvesting on rainy days was that the total number of calendar days to harvest 200 t DM increased from 5 days to 8 days in a dry climate and to 11 days in a wet climate. If the farmer owns the machinery, it is a delay that can very likely be accepted (although the harvested crop will be slightly more mature and less digestible). If the farmer relies entirely on contractual harvesting, the contractor may not be willing to stand idle and not be using the machinery during rainy days.

The "price" of wilting was an even more prolonged harvest period, to 13 days in a dry climate and 18 days in a wet climate. Although wilting was very effective at reducing silage effluent, it is less likely to be practised when harvest machinery is custom operated because of long idle periods. Even farmers with their own machinery will have to balance the benefits of less effluent loss versus a slightly more mature, less digestible crop.

The wilting system assumed 6 h of field wilting with conventional conditioning machinery. A novel wilting system called mat making could reduce wilting time to as little as 2 h for silage making (Savoie and Beauregard 1991). A very rapid wilting system would cause less harvest delay and less loss due to maturity; it could even completely eliminate silage effluent flow.

In view of current legislation in several countries that can penalize stream water pollution by heavy fines, no effluent loss to the environment is the only acceptable level. Even wilting with current conventional methods resulted in occasional small amounts of effluent. Under all harvest systems in horizontal silos, some form of containment is thus necessary. The storage volume may be quite small in a wilted silage system; there should nonetheless always be provisions for collection, storage and disposal of silage effluent from horizontal silos.

Table V. The 95% probability level of maximum effluent over different accumulation periods for 3 harvest systems ensiling 200 t DM. (Rain prob. = 0.3; rainfall = 720 mm/yr; initial DM = 18%)

Harvest system	Effluent (L) accumulated over period			
	1 day	2 days	7 days	Total
1. Direct-cut non-stop	23,800	46,800	136,800	224,400
2. Direct-cut stop-when-raining	10,800	21,400	67,700	134,300
3. Wilted	370	750	2,500	7,200

Table VI. Time (days) required to harvest 200 t DM with 3 harvest systems under 2 rainfall probabilities (RP)

Harvest system	Time (d) with standard deviation in parentheses	
	RP = 0.6	RP = 0.3
1. Direct-cut non-stop	5.00 (0.00)	5.00 (0.00)
2. Direct-cut stop-when-raining	11.26 (3.32)	7.80 (1.74)
3. Wilted	17.96 (3.32)	12.52 (1.75)

CONCLUSIONS

A mathematical model was developed to estimate silage effluent from horizontal silos. It was an exponential decay function with an initial lag and parameters estimated from empirical data. Simulation over a 50-year period with daily rainfall probability and quantity as the main weather variables indicated the following trends:

1. A short 6-hour wilting period was a very effective way of reducing the total amount of silage effluent but it did not entirely eliminate the problem of effluent. There was still a likelihood (1 year out of 20) that a peak effluent flow rate of 600 L per day would be observed on farms harvesting 200 t DM in one cut. This was considerably less than peak flows of 21,800 L per day with a direct-cut system (on non-rainy days only) or 36,900 L per day with a continuous, rain or shine, direct-cut harvest.
2. To ensure that absolutely no effluent will drain into watercourses, all horizontal silos require some form of effluent collection, storage and disposal. Under the worst harvest conditions, a storage capacity of 3 m^3 of effluent per 100 t silage is always adequate for one day

of storage. With a wilted silage system, the peak effluent flow is expected to be 2% of that for a direct-cut harvest system.

3. The harvest period may be prolonged from 5 days with direct-cut to more than 18 days with wilting which may appear too costly as the crop matures and becomes less digestible. In some very wet years, a wilted system might convert, for practical reasons, to a short wilt or even a direct-cut system. An adequate effluent storage volume is required for all horizontal silo systems.
4. The model does not provide answers to more precise questions related to effluent flow such as the role of drainage pipes in horizontal silos, the effect of enzymatic additives, interactions between chop length and moisture, and the degree of compaction or density. However, the model provides an alternative to extensive experimentation in estimating effluent flow in various crop and weather conditions. The model can serve as the framework to evaluate alternate management decisions and weather patterns on the probability of effluent production.

ACKNOWLEDGEMENTS

The author is indebted to the Silsoe Research Institute, Bedford, United Kingdom, for providing facilities to do the present study. He thanks Mr. A.C. Knight and Dr. A.G. Williams of the Silsoe Research Institute, and Dr. M.B. McGechan of the Scottish Centre of Agricultural Engineering for useful comments on the work.

REFERENCES

ADAS. 1984. Silage - avoiding pollution. Booklet 2429. Agricultural Development and Advisory Service, Ministry of Agriculture, Fisheries and Food, UK.

Bastiman, B. 1976. Factors affecting silage effluent production. *Experimental Husbandry* 31:40-46.

Bastiman, B. and J.F.B. Altman. 1985. Losses at various stages in silage making. *Research and Development in Agriculture* 2(1):19-25.

Beard, M., L. Beck, C.J. Clark, R.J. Merriman and D.J. Palmer. 1989. Water pollution by silage effluent. In *Silage Effluent and its Control*, 1-8. Marlow, UK: Chalcombe Publications.

Bridgestocke, T.D.A. 1989. Absorbents and silage effluent. In *Silage Effluent and its Control*, 17-25. Marlow, UK: Chalcombe Publications.

Gordon, F.J. 1981. The effect of wilting on silage composition and its feeding value for milk production. *Animal Production* 32:171-178.

Graves, R.E. and P.J. Vanderstappen. 1993. Environmental problems with silage effluent. In *Proceedings from the National Silage Production Conference*, NRAES-67:291-299. Northeast Regional Agricultural Engineering Services, Ithaca, NY.

Haigh, P.M. 1993. Grass silage effluent production in England and Wales. *BGS Occasional Symposium* 27:147-150. British Grassland Society, Reading, UK.

Jones, D.I.H., R. Jones and G. Moseley. 1990. Effect of incorporating rolled barley in autumn-cut ryegrass silage on effluent production, silage fermentation and cattle performance. *Journal of Agricultural Science, Cambridge* 115:399-408.

Law, A.M. and W.D. Kelton. 1982. *Simulation Modeling and Analysis*. New York, NY: McGraw Hill.

McDonald, P., A.R. Henderson and S.J.E. Heron. 1991. *The Biochemistry of Silage*, 2nd ed. Marlow, UK: Chalcombe Publications.

McGechan, M.B. 1990. Operational research study of forage conservation systems for cool, humid upland climates. Part 1: Description of model. *Journal of Agricultural Engineering Research* 45:117-136.

Offer, N.W., D.G. Chamberlain and M. Kelly. 1991. Management of silage effluent. In *Summaries of Papers of European Grassland Federation Conference: Forage Conservation Towards 2000*, 22-24. FAL, Braunschweig, Bundesallee 50, Germany.

O'Kiely, P. 1990. Factors affecting silage effluent production. *Farm and Food Research* 21(2):4-6.

Pitt, R.E. 1983. Mathematical prediction of density and temperature of ensiled forage. *Transactions of the ASAE* 26(6):1522-1527,1532.

Pitt, R.E. and J.-Y. Parlange. 1987. Effluent production from silage with application to tower silos. *Transactions of the ASAE* 30(4):1198-1204, 1208.

Savoie, P. and S. Beauregard. 1991. Forage mat making: species and compression effects on drying. *Canadian Agricultural Engineering* 33:113-118.

Savoie, P. and A. Marcoux. 1985. Systems alternatives in forage harvest and conservation. *Transactions of the ASAE* 28(5):1378-1384.

Savoie, P., E. Pattey and G. Dupuis. 1984. Interactions between grass maturity and swath width during hay drying. *Transactions of the ASAE* 27(6):1679-1683.

Woolford, M.K. 1984. *The Silage Fermentation*. New York, NY: Marcel Dekker, Inc.

Effect of litter oiling and ventilation rate on air quality, health, and performance of turkeys

J.J.R. FEDDES[1], K. TASCHUK[1], F.E. ROBINSON[1] and C. RIDDELL[2]

[1]Department of Agricultural, Food and Nutritional Science, University of Alberta, Edmonton, AB, Canada T6G 2P5; and Department of Veterinary Pathology, Western College of Veterinary Medicine, University of Saskatchewan, Saskatoon, SK, Canada S7N 0W0.

Received 20 August 1993; accepted 15 January 1995.

Feddes, J.J.R., Taschuk, K., Robinson, F.E. and Riddell, C. 1995. **Effect of litter oiling and ventilation rate on air quality, health, and performance of turkeys.** Can. Agric. Eng. 37:057-062. An experiment was conducted with male heavy turkeys to study the effects of the application of canola oil to litter and ventilation rate, on health status and growth performance at 16 weeks of age. Litter oiling and increased ventilation rate significantly reduced the concentration of aerosol dust particles and the incidence of lung lesions. Overall, birds that developed lung lesions were those which had a fast rate of growth initially (8 to 12 weeks of age). Such birds later exhibited a relatively slow rate of growth (12 to 16 weeks of age). There would appear to be a negative relationship between the development of lung lesions and subsequent growth rate. Litter oiling offers a practical means of reducing dust in poultry housing.

Une expérience était conduite avec les dirdons pesant pour de étudier les effets de l'application de l'huile de canola á la litière, et la vitesse de ventilation sur la condition de santé et la performance de la croissance á 16 semaines d'âge. L'huilage de la litière et une vitesse de ventilation augmentée avaient redurent significativement la concentration des particules de la poussière aéroportée et l'incidence des lésions due poumon. Les dindons qui ont développés les lésions du poumon étaient seul qui avaient une croissance rapide initialement (8 á 12 semaines d'âge). Ces dindons avaient exhibités deniernment une croissance plus lent (12 á 16 semaines d'âge). Ca semble d'être un rapport négatif entre le développement des lésions du poumon et la croissance subséquent. L'huilage de la litière offert un moyen pratique de réduire la poussière dans la grange de volaille.

INTRODUCTION

Poultry raised under conditions of confinement housing can be subjected to a complex mixture of aerial contaminants comprised of airborne dust, viable micro-organisms, ammonia, carbon dioxide, and water vapour. Two routes can be followed to achieve a reduction in the level of aerial contamination in such housing. Firstly, an environment can be improved by diluting the aerial contaminants through ventilation to an acceptable concentration or secondly, by reducing the rate of release of such contaminants from the litter.

There is evidence that the well-being, productivity, and health of people and animals can be adversely affected by high levels of aerial contaminants (Wolfe et al. 1968; Janni et al. 1985; De Boer and Morrison 1988). Donham et al. (1988) have reported that respiratory function in stockpersons may be impaired due to high concentrations of airborne dust and ammonia. Nagaraja et al. (1983) reported on the adverse effects of ammonia concentrations of 10 and 40 ppm on tracheal tissues of turkeys. Excessive mucus production, matted cilia, and areas of deciliation in the tracheal tissues were detected after exposure to such conditions. Feddes et al. (1992a) found that turkeys housed from 12 to 20 weeks of age at a relatively low rate of ventilation (2.9 L/s per bird) exhibited lower body weights and a higher incidence of lung lesions than did turkeys that were subjected to a high (13.3 L/s per bird) ventilation rate. Feddes et al. (1992b) reported that the majority of the airborne dust particles in turkey housing is of fecal origin, with urates being the major contributor. The nitrogen content of the dust was found to be excessive and may be a contributing factor in the occurrence of lung lesions.

One potential method of suppressing dust production is the weekly application of canola oil to litter, since litter is considered to be a major source. Takai et al. (1993) reported using rapeseed oil to reduce dust levels in pig housing by 50-90%. The primary objective of the research reported here was to determine the effects of applying canola oil to litter and ventilation rate on air quality and the growth performance and health status of male heavy turkeys to 16 weeks of age. Air quality was evaluated in terms of the concentrations of ammonia and dust as well as relative humidity. Turkey performance and health were determined from body mass gain and feed efficiency data in addition to the incidence and severity of lung lesions. The study investigated the effects of the application of canola oil at ventilation rates typical of spring-fall, winter, and summer.

MATERIALS AND METHODS

Facilities

Four environmental chambers located within a turkey barn at the University of Alberta's Edmonton Research Station were used to conduct the research. Each chamber was 3.4 x 4.0 x 2.4 m in size with a floor area of 13.6 m^2. Each chamber was ventilated by a variable speed exhaust fan to provide spring-fall, summer, and winter ventilation rates. A recirculation duct and counter balance continuous slot inlet ensured complete mixing of incoming air with the resident air (Fig. 1). A 60-W incandescent light bulb provided illumination (23 hours of light: 1 hour of dark). Two bell-type waterers and three conventional circular

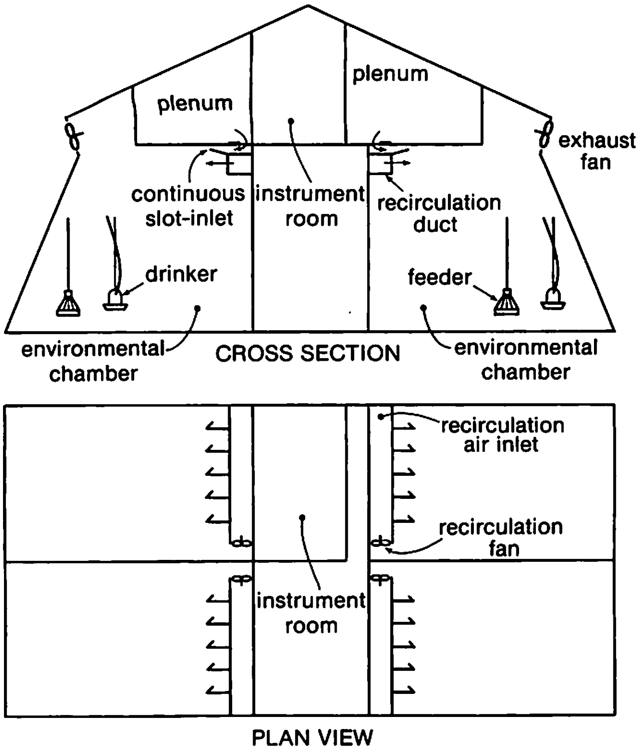

Fig. 1. Cross-section and plan view of the four environmental chambers.

feeders were suspended within each chamber.

The plenum was supplied with 1.65 m^3/s of outside fresh air which was heated by a natural gas furnace. A thermostat located in one of the chambers maintained a common set-point temperature for all four chambers. An 1.2 kW electrical heater was installed in each of the other rooms to ensure that the set-point temperature was maintained.

Air quality assessment

The environment of each chamber was monitored once per week for a 24-hour period. Measurements included: carbon dioxide, oxygen and ammonia concentrations, dry-bulb temperature, dewpoint, and dust concentration for particles of less and greater than 5μm. Measurements were taken in the plenum and in all four chambers. Ventilation rates were measured prior to each run by measuring air speeds in a discharge duct located downstream from each exhaust fan. Air velocities (± 0.2 m/s) were measured by a constant-temperature thermal anemometer (Velocicalc, TSI, St. Paul, MN). Dry-bulb temperatures (± 0.2°C) were measured with the use of thermistors (Fenwal Electronics, Framingham, MA). Dewpoints (± 1°C) were measured by a dewpoint hygrometer (General Eastern, Watertown, MA). Ammonia (± 5 ppm) and carbon dioxide (± 100 ppm) concentration were measured by non-dispersive infrared analyzers (Beckman Industrial, Model 880, La Habra, CA) while oxygen levels (±100 ppm) were measured by a paramagnetic oxygen analyzer (Servomex, Model 540A, Sussex, England). Oxygen concentrations were corrected for moisture content. Carbon dioxide, oxygen, and ammonia concentrations and dewpoints were measured alternately on a four-minute basis once each hour between the four chambers and the plenum. Gas samples were drawn to the analyzers via sample tubes connected to solenoid activated valves that were controlled by a datalogger. The tubes were connected to a vacuum pump downstream from each valve that delivered sample air to each analyzer at prescribed rates controlled by flow meters. The datalogger scanned the outputs from the analyzers as well as the thermistors prior to switching to the next sampling location. The datalogger was connected to an IBM-PC which recorded the temperatures and gas concentrations.

Dust concentrations were measured by an aerodynamic particle sizer (TSI, St. Paul, MN). Sample tubes from the four chambers and the plenum were connected to a ball valve assembly which was controlled by an I/O board connected to an IBM personal computer. Each sampling location was sampled 4 min/h. Prior to switching sampling locations, the dust concentrations were recorded. All equipment was housed in a laboratory located in the plenum directly above the chambers (Fig. 1).

Stocks and management

Male Hybrid-strain tom turkeys were obtained commercially and were raised to 8 weeks of age in another environmentally-controlled turkey brooding facility. At 8 weeks of age, the birds were wing-banded and randomly assigned to one of the four chambers described above. Initially, each chamber housed 75 turkeys with a stocking density of 5.5 birds/m^2. The birds had *ad libitum* access to feed and water throughout the experiment. Commercial-type turkey starter and grower diets were fed in mash form in accordance with National Research Council requirements (National Research Council 1984).

The birds were individually weighed at 8, 12, and 16 weeks of age. Feed consumption was recorded for the intervals of 8 to 12 weeks and 12 to 16 weeks. At 12, 13, 14, and 15 weeks of age, five or six birds were removed from each pen to maintain a similar bird mass in each pen throughout these weeks of the experiment. Hence, at 16 weeks of age, there were approximately 50 birds in each pen at a stocking density of 3.7 birds per m^2. The mass of these birds and the mass of all mortality were taken into account in the calculation of feed efficiency.

At 16 weeks of age all remaining birds were shipped to a commercial abattoir. During processing, all lungs were removed, identified as to bird of origin by wing band number, and stored on ice pending examination for the incidence of lung lesions as described previously (Feddes et al. 1992a). The experiment consisted of two treatments (oiled and untreated litter) and three ventilation rates (summer, winter, and spring-fall) representative of the range normally used in Western Canada. Two flocks of birds were used in the experiment utilizing the rooms two times. The chambers housing the first flock were ventilated at spring-fall rates. From 8 to 12 weeks of age, the ventilation rate was 4.8 L/s per bird and increased to 6.7 L/s per bird during weeks 13 to 16, due to increased bird mass. For the second flock, two chambers were ventilated at summer rates while the remaining two were ventilated at winter rates. From 8 to 12 weeks of age