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A Science Based PM_{10} Emission Factor for Freestall Dairies

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Abstract. *There is currently little published data on particulate matter (PM) emission rates (factors) from dairies. The philosophy of some State Air Pollution Regulatory Agencies (SAPRA's) is to use the emission factor that had been published in AP-42 for cattle feedyards of 280 lbs/1000 head per day (lb/1000hd/d) total suspended particulate (TSP) matter or 70 lb/1000hd/d* PM_{10} *for permitting and emissions inventory purposes. Prior to EPA removing this cattle feedyard emission factor from AP-42, the Department of Biological and Agricultural Engineering at Texas A&M University had determined that a more appropriate emission factor for cattle feedyards in the relatively arid west Texas area was 19 lb/1000hd/d (uncorrected for rainfall and snow events). The source of PM from cattle feedyards and dairies is the open surface of the pens (manure pack). The major difference between dairies and cattle feedyards is the fraction of time the dairy herd is in contact with the manure pack relative to cattle on feed. Previous work has shown that an appropriate emission factor for freestall dairies would be 17.8 lb/1000hd/day. The goal of this research is to expand on the previously developed emission factor using Industrial Source Complex and incorporating more data.*

Keywords. PM_{10}, $PM_{2.5}$, total suspended particulate, air sampling, emission rate, freestall dairy, emission factor, emissions inventory

Introduction

The agriculture industry is coming under increased scrutiny as a pollution source. This is especially true in non-attainment areas. The San Joaquin valley in California is classified as a serious non-attainment area for PM_{10}. State Air Pollution Regulatory Agencies (SAPRA's) are required to include in their respective State Implementation Plans (SIP) procedures whereby non-attainment areas will be brought into attainment. These procedures are based upon emissions inventories, permitting, and emission factors. This is a problem specifically in California due to the dairies' locations in PM_{10} non-attainment areas. The focus of the SIP is on reducing pollution from the largest sources. If the dairy emission factor is grossly in error, the emissions inventories for PM_{10} from dairies will be in error. If the SIP plan for bringing the PM_{10} non-attainment areas into attainment is based upon erroneous emissions inventories, it is unlikely the area will be brought into attainment. In order to reduce PM_{10} emissions from dairies, the SAPRA will likely require that additional controls be installed with the permitting process. The economic burdens of reducing PM_{10} emissions from dairy operations will likely result in more dairies being forced out of business. It is imperative that accurate PM_{10} emission factors be used by SAPRA's for emissions inventory and permitting purposes.

Peters and Blackwood (1978) developed an emission factor of 127 kg/1000hd/day total suspended particulate (TSP) matter (280 lb/1000hd/d TSP) for feedyards. This work was done using sampling data from Algeo et al., (1972) which represented the only data available at the time. Sweeten et al (1989, 1998) demonstrated that 25% of the TSP emitted by cattle feedyards was PM_{10} which was accepted by the EPA. Hence, the PM_{10} emission factor used by SAPRA's for permitting and emissions inventory purposes was 32 kg/1000hd/d (70 lb/1000hd/d PM_{10}) The errors associated with the AP-42 emission factor based upon Peters and Blackwood's study were documented by Parnell et al (1999). Subsequent work by Texas A&M University (Parnell et al., 1999) has shown that a more appropriate number would be 6.8 kg/1000hd/day PM_{10} (15 lb/1000hd/day PM_{10}).

Feedlots for beef cattle are open pens with the pen surface serving as the manure pack. The action of the cattle on the manure pack is the source for PM emissions from the facility. Conversely, freestall dairies will keep the lactating portion of their herd in freestall barns with the rest of the cattle being kept in pasture areas or open pens similar to feedlots. A typical freestall barn consists of a feed alley down the center with feed bunks on each side. The exercise pens are only used during nighttime hours, and have the same surface composition as the open pens. Manure primarily accumulates in the alleys and is removed in one of two ways: flushing or scraping. Flushing involves introducing a large volume of water into the alley, which flows into a collection system. It is performed multiple times daily in order to minimize manure accumulation in the alleys. Scraping of the pens is a control method used to reduce PM emissions. The frequency of scraping will vary from dairy to dairy. The frequency of manure removal in the free stall alleys minimizes PM entrainment from this section of the dairy. Previous work by Goodrich et al., (2002) showed that the herd wide, temporally averaged emission factor is 8.1 kg/1000hd/day TSP. This was accomplished using the box model as described by Flocchini et al., (2001).

Methods:

Data for this study was collected at the same dairy in central Texas as the previous work by Goodrich et al., during one week in June, 2003. The dairy herd consisted of 1840 milking cattle with a total of 2,200 head of cattle on property. The lactating herd is kept in a series of three freestall structures and two open pens. Each freestall housed approximately 460 cattle and the two open pens housing approximately 230 cattle each. The layout of the dairy is presented in Figure 1. The low producing cattle are kept in open pens one and two while the remainder of the lactating herd is kept in the freestalls during the day. They are allowed into the exercise pens at dusk. The axis of the facility lies along a line that is approximately 15 degrees west of due north. The prevailing wind direction was from the south, south-east during the entire sampling period allowing for similar placement of samplers as the previous work. The dairy was operating under normal conditions during the sampling period except for the final stages of construction on a new milking parlor which was determined as not a significant source of emissions.

Sampling was conducted using high-volume (TSP) samplers that were designed by Texas A&M University to meet EPA reference device specifications as described by Boriack et al., (2003). Sampling intervals ranged from two to four hours. Ambient meteorological conditions were monitored using an Onset HOBO Weather Station to be used for computation of flow data as well as dispersion modeling inputs.

Emission Rate Calculations:

Measured concentrations were used to calculate emission factors using two independent methods. First, the box model was used to determine a herd wide emission factor. The second method used was the EPA approved Industrial Source Complex Short Term version 3 (ISC). This model affords the ability to use different emission fluxes for differing areas. In order to determine the fluxes, the samplers in two downwind locations were used. Sampler location D1 is located on the north-western edge of the open lots and was used in ISC to determine the emission flux from the open lot area. Sampler D2 was located at the northern edge of the facility and was used in ISC to determine the flux from the freestalls as well as in the box model to determine the facility wide emission factor. Net concentrations were used for all emission flux calculations and were determined by subtracting measured upwind concentration from the measured downwind concentration. The upwind sampler was located on the east side of the facility with open hay fields upwind of the sampler.

Box Model Flux:

In order to use the box model some parameters must be determined in order to calculate the emission flux from the source of interest. The box width is defined by the maximum width of the source area. The width of the dairy at the downwind sampling site was 140 meters. It was assumed that the height of the plume (box) corresponded to σ_z at 50 meters downwind from the source for a stability class of ‘C’ (4 meters). The height of the box for all calculations was 4 meters. For preliminary calculations of emission factors, the box dimensions were 140 meters by 4 meters. Equation 1 was used to calculate the emission rates of PM from the area upwind of the sampler for each acceptable measured concentration. Net concentration was determined by subtracting upwind sampler concentrations during the respective test periods from the downwind sampler. The meteorological conditions were considered to be conducive for the box model if the average flow vector (direction the wind is blowing) during the sampling period was between 300 degrees and 30 degrees. This represents a range of plus or minus 45 degrees from ideal.

$$ER = W \bullet H \bullet U \bullet C \bullet 10^{-6} \qquad \text{(Equation 1)}$$

where

- ER=emission rate, g/s;
- W=width of box, 140 meters;
- H=height of box, 4 meters;
- U=average wind speed during sampling period, m/s; and
- C=net measured concentration, µg/dscm.

To determine the emission factor, the emission rate was divided by the known number of cattle upwind of the sampler and converted to a 24-hour basis[1] using Equation 2.

$$EF = \frac{ER}{N} \bullet 86{,}400 \qquad \text{(Equation 2)}$$

where

- EF=emission factor, g/1000hd/day;
- ER=emission rate, g/s
- N=number cattle/1000 in upwind pens; and
- 86,400 = conversion factor.

This method allows for the calculation of a single emission factor for all cattle upwind of the sampler location. For all tests it was assumed the total number of cattle upwind was the entire milking herd of 1860 cattle.

Industrial Source Complex:

This model is a steady state Gaussian plume model that can be used to predict downwind concentration from area sources (EPA, 1995). It calculates 1-hour average concentrations at receptor locations placed around the source. To determine the concentration at a receptor down wind of an area source ISC integrates the basic Gaussian equation over the area of the source as shown in equation 2 (EPA, 1995).

[1] The measured concentrations were for 2 to 4 hour periods. In effect, the individual emission factors corresponded to the time period when sampling occurred. For comparison purposes, all emission factors were converted to a 24-hour basis.

$$C = \frac{Q_A}{2\pi u_s} \int_X \frac{V}{\sigma_y \sigma_z} \left(\int_Y \exp\left[-0.5 \left(\frac{y}{\sigma_y} \right)^2 \right] dy \right) dx \qquad \text{(Equation 3)}$$

where

- C = concentration of pollutant (μg/m^3),
- Q_A = pollutant emission rate (μg/s^1-m^{-2}) (represented as EF in the box model),
- V = vertical term used to describe vertical distribution of the plume,
- σ_y, σ_z = Pasquill-Gifford plume spread parameters based on stability class,
- u_s = 1 hour average wind speed at pollutant release height (m/s),
- X = upwind direction, and
- Y = cross wind direction.

ISC integrates the point source equation over the area of the source that is upwind of the receptor location. Therefore, receptors can be placed anywhere around or inside a source. The only limitation is the σ_z component goes to zero as the receptor distance approaches zero. This causes inconsistent results as the downwind distance (X) approaches 0. It is recommended that receptors be placed more than 1 meter from any source. As the distance upwind of the sampler increases the vertical plume spread becomes very large. This large spread reduces the impact of that location on the measured concentration.

The plume-spread parameters (σ_y and σ_z) are functions of the Pasquill-Gifford stability class and downwind distance from the source. They assume a normal distribution of the plume in the vertical and horizontal directions. The use of the Gaussian model for elevated point sources assumes infinite dispersion of the plume in both directions as distance increases. The problem is that ground level area sources cannot have the plume extending below ground level. ISC corrects for this by reflecting the portion of the plume that is below ground level back above the ground. Therefore, ISC predicts the highest concentration at ground level (Meister, 2000).

In order to compute the emission factor using ISC it was necessary to layout the facility and determine the separate emitting areas of the facility. For example, the open lots were considered to have a significantly higher emission rate than the freestall areas. Once the facility was laid out in ISC it was then a matter of determining the emission rates for each area and their interactions. Due to the layout of this facility and the observed wind patterns there was no confounding contribution between the two sources. There is no contribution to sampler D2 while the open lot is being modeled and conversely no contribution to sampler D1 when only the freestalls were modeled. This allowed for the determination of the each emission factor independently.

The traditional use of ISC in the regulatory field is to determine downwind concentrations from sources in question in order to determine compliance with national and local regulations. Therefore, the operation of ISC requires the input of emission fluxes and meteorological data along with the layout of the facility and receptors to determine concentration. To determine a flux in ISC an initial flux is input to determine a base concentration at the sampler location. In this case the input flux used is 1 μg/m^2-s. This yielded the ISC modeled concentration that is then scaled using equation 4 to determine the emission flux for that test period.

$$EF = BF \bullet \frac{MC}{BC} \qquad \text{(Equation 4)}$$

where

- EF = emission flux for specific test (μg/m^2-s),
- BF = base emission flux (1 μg/m^2-s),
- MC = measured concentration (μg/m^3), and
- BC = ISC base concentration (μg/m^3).

To convert the emission flux for a specific test to that of kg/1000hd/day equation 5 was used.

$$Factor = \frac{EF}{Area} \bullet Spacing \bullet 86{,}400 \quad \text{(Equation 5)}$$

where

- Factor = Emission factor (kg/1000hd/day),
- EF = emission flux for specific test (μg/m^2-s),
- Area = Spacing of cattle (m^2/1000hd), and
- 86,400 = conversion factor.

the This process was done for each test with usable data. This allowed for an emission factor to be developed for each test. An emission factor was calculated for each concentration measurement that resulted in a net concentration greater than zero. It was anticipated (based upon previous experience with cattle on feedyards) that the emission rates would vary significantly during the day. It was assumed that short-term measured concentrations would be directly proportional to the corresponding emission factor for the time period sampled. In order to obtain an estimate of the 24-hour emission factor, it was essential to not average emission factors for the time periods when emission rates were always low or high. The 24-hour emission factor was calculated by equally weighting the measured emission factors for each of the 6-hour time periods.

To convert the TSP emission factors to PM_{10}, it was assumed that the characteristics of the PM from the dairy were the same as the PM emitted by cattle feedyards. For a cattle feedyard, the PM_{10} emission rate is equal to 25% of the TSP emission rate (Sweeten et al, 1989, 1998).

Results and Discussion:

Both methods were used to calculate a herd wide emission factor. ISC was used to determine an emission factor for each source (freestall and open lot) and then a weighted average was used as the facility wide emission factor. The box model gives an emission factor for all sources upwind of the sampler being used. Table 1 is a summary of the emission factor calculations for the entire facility using the box model and sampler D2. The average emission factor is 10.2 kg/1000hd/day not weighted for time periods.

Table 1. Net measured concentrations of sampler D2 with the corresponding average wind speed and direction for each test. The emission factor using the box model is presented along with the time period that the test was used in.

Test #	Net Measured Concentration (µg/am^3)	Flow Vector (degrees)	Wind Speed (m/s)	Emission Factor (kg/1000 hd/day TSP)	Time Period
2	51.6	307.5	3.1	4.2	4
3	69.3	311.8	2.8	5.1	1
4	52.7	330.4	3.0	4.2	1
5	212.7	324.6	4.0	22.5	2
6	127.7	335.1	4.2	14.2	3
7	361.1	336.2	3.9	37.1	3
8	90.3	314.6	2.9	6.9	4
9	32.2	321.3	4.3	3.7	1
10	60.9	336.0	3.6	5.8	1
11	117.6	359.0	3.7	11.5	2
12	74.0	354.1	4.1	7.9	3
13	67.1	337.9	3.4	6.1	3
14	66.4	321.2	2.1	3.7	4
Average	106.4	N/A	N/A	10.2	N/A

The calculated emission factors were grouped into the time periods and an average emission factor was calculated for each time period. Table 2 shows the average emission factor for each time period and the corresponding time weighted facility emission factor as determined by the box model. This emission factor corresponds to the entire facility and represents a time weighted average of the two emission sources on the dairy.

Table 2. Time period and overall TSP emission factors as calculated by the box model (kg/1000hd/day)

Time Period	12am-6am	6am-Noon	Noon-6pm	6pm-12am	Weighted Average
Box Model Emission Factor	4.7	17.0	16.3	4.9	10.7

The emission factor of 10.7 kg/1000hd/day TSP represents the 24-hour TSP emission factor for this dairy. It corresponds to an emission factor of 2.7 kg/1000hd/day PM_{10}. The variation in emission factors throughout the day can be attributed to the change in animal activity. The low calculated emission factor for the first time period can be attributed to the small amount of activity during the early morning hours. During the second and third time periods, activity increased with increased activity by employees and operations on the dairy. The final time period represents the cattle spreading out from the shelters and bedding down for the night.

In calculating an emission factor using ISC it is possible to apply different emission fluxes to the two distinct area sources. Both emission sources were modeled separately using the base emission flux and actual meteorological conditions. The base flux is then scaled to by the ratio of the modeled to actual concentration in order to determine the actual flux for that test period.

Table 3. Net measured concentrations at sampler D2 and the corresponding emission factor as determined by ISC for the freestalls. The Base concentration is the concentration predicted by ISC using 1μg/m^2-s as the emission flux. The scalar column represents the actual emission flux required for that test to model the actual measured concentration.

Test #	Net Measured Concentration (μg/am^3)	ISC Base Concentration (μg/am^3)	Scalar (Net/ISC)	ISC Emission Factor (kg/1000hd/day)
2	51.6	13.3	3.9	2.9
3	69.3	14.6	4.7	3.6
4	52.7	19	2.8	2.1
5	212.7	8.94	23.8	18.0
6	127.7	10	12.8	9.6
7	361.1	11.2	32.2	24.4
8	90.3	15.7	5.8	4.3
9	32.2	9.65	3.3	2.5
10	60.9	18.9	3.2	2.4
11	117.6	22.7	5.2	3.9
12	74.0	10.2	7.3	5.5
13	67.1	13	5.2	3.9
14	66.4	22.4	3.0	2.2
			Average	6.6

The ISC time weighted emission factor for the freestall portion of the dairy is 6.9 kg/1000hd/day TSP or 1.73 kg/1000hd/day PM_{10}.

Table 4. Time weighted average emission factor (kg/1000hd/day TSP) for the freestall as determined by ISC.

Time Period	12am-6am	6am-Noon	Noon-6pm	6pm-12am	Weighted Average
ISC Free Stall Emission Factor	2.7	10.9	10.8	3.2	6.9

The open lots were modeled using sampler D1 with the same process as the freestalls and an emission factor was determined for each test. The ISC calculated time weighted freestall emission factor for PM_{10} is 1.7kg/1000hd/day.

Table 5. Net measured concentrations at sampler D1 and the corresponding emission factor as determined by ISC for the open lot. The Base concentration is the concentration predicted by ISC using 1μg/m^2-s as the emission flux. The scalar column represents the actual emission flux required for that test to model the actual measured concentration (μg/m^2-s).

Test #	Net Measured Concentration (μg/am^3)	ISC Base Concentration (μg/am^3)	Scalar Net/ISC	ISC Emission Factor (kg/1000hd/day)
2	171.3	23.3	7.4	27.2
3	111.5	25.7	4.3	16.0
4	66.6	22.3	3.0	11.0
5	211.7	14	15.1	55.9
6	108.1	9.9	10.9	40.4
7	67.3	10.5	6.4	23.7
8	40.6	27.7	1.5	5.4
9	82.9	17.9	4.6	17.1
10	30.2	18.1	1.7	6.2
12	52.6	6.9	7.6	28.2
13	59.6	13.3	4.5	16.6
14	223.3	69.4	3.2	11.9
15	45.2	61.8	0.7	2.7
			Average	20.2

Table 6. Time weighted average emission factor (kg/1000hd/day TSP) for the open lot as determined by ISC.

Time Period	12am-6am	6am-Noon	Noon-6pm	6pm-12am	Weighted Average
ISC Open Lot Emission Factor	10.6	55.9	27.2	14.8	27.1

The herd wide ISC emission factor is calculated by weighting each emission factor by the number of cattle that are in each emitting category. The time weighted PM_{10} emission factor is 6.8kg/1000hd/day.

Table 7. Overall ISC emission factor for the freestall dairy weighted for both time and number of cattle in each category.

Location	Number of Cattle (Thousands)	Emission Factor (kg/1000hd/day
Freestall	1.38	6.9
Open Lot	.46	27.1
Average Emission Factor		11.9

The two methods of finding the emission factor from a measured concentration are totally independent but yield very similar emission factors. This verifies that the box model is an effective method for determining emission factors as compared to ISC.

Conclusion:

From sampling conducted at a central Texas Dairy it has been shown that an emission factor for the freestall dairy would be 11.3kg/1000hd/day TSP (3.0 kg/1000hd/day PM_{10}). This number does not represent the variation that will occur throughout the year as ground conditions change, though it is much more representative of PM_{10} emissions from a freestall dairy than the current feedyard emission factor of 32 kg/1000hd/day PM_{10} (70 lb/1000hd/d) that has been used by some SAPRA's. Though, this emission factor does account for the temporal variations that may occur during hot dry periods around the country.

References:

Algeo, J. W., C.J. Elam, A. Martinez, and T. Westling. 1972. How to control feedlot pollution: Bulletin D. California Beef Cattle Feeders Association, Bakersfield, California.

Boriack C. et.al, 2003. Revised Design of the Total Suspended Particulate Sampler. Presented at the Beltwide Cotton Conference, Nashville, TN. 2003

EPA. 1995. Compilation of air pollutant emission factors, Volume I: Stationary point and area sources, Fifth edition. January 1995. U.S. EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Flocchini, R. G., T. A. James. 2001 Interim Report Sources and Sinks of PM_{10} in the San Joaquin Valley. A study for United States Department of Agriculture Special Research Grants Program. Air Quality Group Crocker Nuclear Laboratory, University of California, Davis, Davis, CA.

Goodrich L.B., Preliminary PM_{10} Emission Factor For Freestall Dairies. ASAE Paper No. 024214. St. Joseph, Mich.: ASAE.

Parnell, S., et al. 1993. Dispersion modeling for prediction of emission factors. Paper No. 934554 presented at the 1993 International Winter Meeting sponsored by the American Society of Agricultural Engineers, Chicago, IL. American Society of Agricultural Engineers, St. Joseph, Mi.

Parnell, S., et al. 1995. Dispersion modeling for prediction of emission factors from cattle feedyards. Texas Agricultural Extension Service, Texas A&M University System, Report for Environmental Protection Agency, Research Triangle Park, NC. Department of Agricultural Engineering, Texas A&M University, College Station, Tx.

Parnell, S. 1994. Dispersion modeling for prediction of emission factors for cattle feedyards. Unpublished Master of Science Thesis. Department of Agricultural Engineering, Texas A&M University. College Station, Texas.

Parnell, C. B., Shaw, B. W., and Auvermann, B. W. 1999, Agricultural Air Quality Fine Particle Project: Task 1 – Livestock Feedlot PM Emission Factors and Emissions Inventory Estimates Final Report. Research sponsored by the Texas Natural Resource Conservation Commission. Department of Biological and Agricultural Engineering, Texas A&M University, College Station Texas.

Peters, J.A. and T. R. Blackwood. 1977. Source assessment: beef cattle feedlots. EPA-600/2-77-107. Monsanto Research Corporation, Dayton, OH for EPA Office of Research and Development, Industrial Environmental Research Laboratory, Research Triangle Park, NC.

Sweeten, J. M., C. B. Parnell. 1989. Particle size distribution of cattle feedlot dust. Paper No. 89-4076 presented at the 1989 International Summer Meeting of the American Society of Agricultural Engineers, Quebec, Canada

Sweeten, J. M.; C. B. Parnell, Jr.; B. W. Shaw; and B. W. Auvermann. 1998. Particle size distribution of cattle feedlot dust. Transactions of ASAE. Vol. 41(5): 1477-1481. St. Joseph, Mich.

Sweeten, J. M. 2000. Personal Communication.

Wark, W. and C. F. Warner. 1981. Air Pollution - Its origin and Control. (Second edition). Harper Collins Publishers. New York, N. Y.

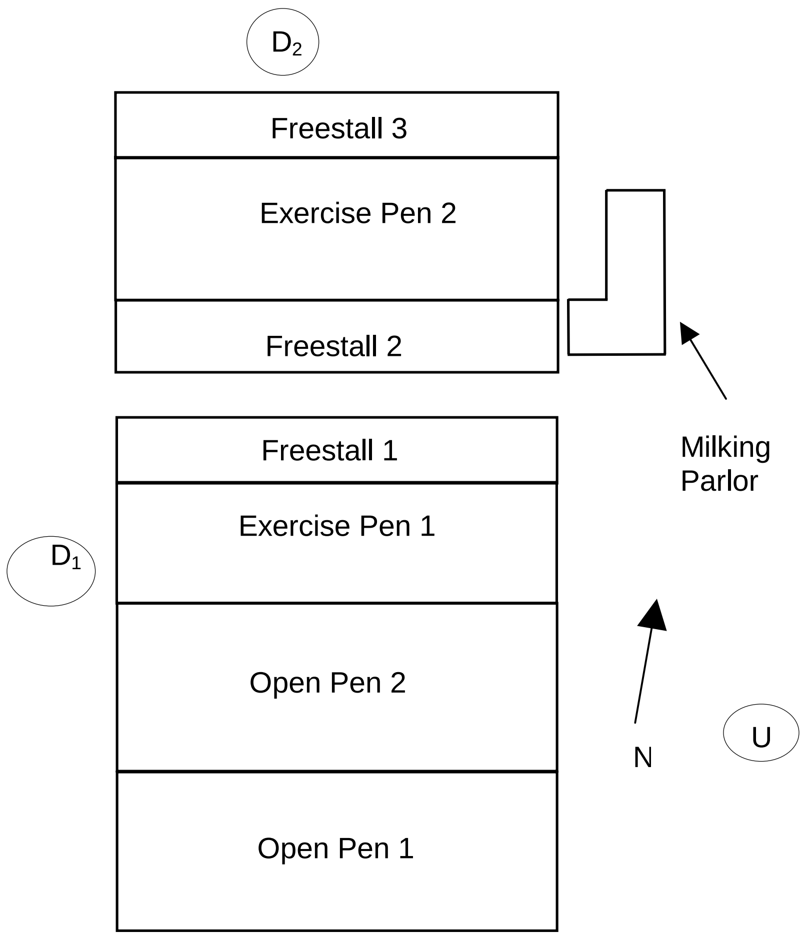

Figure 1. Schematic of the configuration of pens, milking parlor, and freestalls, and relative locations of upwind denoted by ‘U’, and downwind denoted by ‘D’ (D_1, and D_2). Samplers are indicated with ovals.