NM-Manure: A Seasonal Prediction Model for Manure Excretion by Dairy Cattle in New Mexico

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ABSTRACT

More accurate estimates of dairy cattle manure excretion are needed for manure management, nutrient plans, renewable bioenergy production, and environmental assessment. Consequently, it is important to quantify manure excretion by dairy herds. Current estimates use only a few animal groups and average herd characteristics to estimate fixed rates of manure excretion throughout the year. However, manure excretion varies seasonally and should be predicted based on dynamic herd group characteristics. In addition, improved prediction parameters should be incorporated. This study describes the creation of a stochastic dynamic herd model to predict seasonal manure excretion according to herd characteristics regarding milk production, pregnancy rates, and culling rates using improved prediction parameters. The Markov-chain model employed here defines more than 1,400 cow-states according to parity, month in milk, and pregnancy status, and includes season of the year according to pregnancy and culling rates. Although overall estimates of our model were not substantially different from those achieved by commonly used approaches, strong seasonal variations in manure excretion found with our model are missed when using other approaches. Our model also gives the opportunity to tailor dairy farm-specific parameters such as milk productivity, pregnancy rates, and culling rates to obtain more accurate predic-
tions. Predictions of the seasonal variation in dairy manure excretion aid in addressing issues related to manure use and recycling needs, bioenergy production, and assessment of environmental impacts.

INTRODUCTION

More accurate estimates of dairy cattle manure excretion are needed for manure management, nutrient plans, renewable bioenergy production, and environmental assessment. Manure excretion is unavoidable and an intrinsic part of any dairy farm production system. The specific amounts of manure excreted, however, vary substantially, and this is not well understood. Amounts of manure excretion are usually estimated using standard parameters and average herd characteristics (Sporcic et al., 2006; ASABE, 2005; Van Horn et al., 2001, 2003). However, parameters are periodically revised, and new models are being developed (Karmakar et al., 2007) to better understand herd dynamics and manure excretion characteristics.

An understanding of the seasonality of manure excretion is also critical for determining opportunities for manure use (Cabrera et al., 2006). For example, higher amounts of manure nutrients can be recycled in crop fields during spring and summer when plants are most actively growing, and potential of renewable energy produced from manure would decrease towards late summer when lesser quantities of manure are excreted.

Better prediction equations have become available. For example, Weiss (2004) presented equations of manure prediction based on dry matter intake (DMI) and milk production from 232

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Table 1. Variables of the New Mexico Manure Model in Alphabetical Order

Variable (unit/month)[1]	Definition
DY_m (number)	days in month m
F	factor proportional to the difference between actual and calculated herd milk production
i (number)	months of milk production after calving (1–20, mature cows) or months of age (1–32, heifers)
j (number)	months of pregnancy (0–9, unbred or up to 9 months pregnant)
l (number)	lactation or parity (0–9, heifer or up to 9 lactations)
LW (kg)	animal live weight
m (month)	month of the year (1–12, from January to December)
$MC_{l,i,j}$ (head)	cows in lactation l, month in milk i, and month of pregnancy j
M_e (kg/day)	manure excreted by dairy cattle
M_e^d (kg/day)	manure excreted by dry cows
M_e^m (kg)	manure excreted by milking cows
M_e^{farm} (kg)	manure excreted by milking and dry cows
$MK_{i,m,l}$ (kg/day)	milk production for cows in i months in milk, during m month of the year, and in l lactation
$MILK_m$ (kg)	herd milk production
RHA (kg/yr)	rolling herd average, 12-month moving herd average of milk production
$CU_{i,m,k}$ (%)	probability of culling cows with i months in milk, during month m of the year, and in k lactation
$PG_{i,m,k}$ (%)	probability of pregnancy for cows with i months producing milk during month m of the year and k lactation

[1]Unless otherwise stated

treatments in Ohio. Nennich et al. (2005) compiled data from around the United States and parameterized prediction models that resulted in better prediction characteristics of manure excretion using milk production and DMI rather than body weight. Work by Weiss (2004) and Nennich et al. (2005) has contributed to major advancements in current standards (USDA, 1992; ASABE, 1999, 2005), and has provided increased accuracy in manure prediction. These improved prediction equations should be incorporated into models for predicting manure excretion.

The objective of this research was to develop a stochastic dynamic model of herd performance to predict seasonal manure excretion by using local herd characteristics and improved predictor parameters. The goal was to create a baseline model for New Mexico conditions for integration with other dairy farm components to assess whole dairy farm opportunities for manure use and recycling.

MATERIALS AND METHODS
This study integrates a newly created simulation model of herd dynamics for New Mexico with the current parameterizations of manure excretion (Nennich et al., 2005) to predict manure excretion at the farm level, based on cow production stage and seasonality.

Stochastic Simulation of Milking Cow Dynamics
A Markov-chain approach (St-Pierre & Thraen, 1999; deVries, 2004; Cabrera et al., 2006) simulates the dynamics of the dairy herd by calculating the number of milking cows (MC) in each of more than 1,400 definable cow production stages, by month. From these variables manure excretion is calculated. Cow production state is characterized by three dimensions: lactation or parity (l, 1 to 9), month in milk (i, 1 to 20), and month of pregnancy (j, non pregnant 0 to 9 months pregnant). For example, $MC_{2, 10, 5}$ denotes a group of cows in second lactation with 10 months in milk and five months pregnant. Table 1 contains a list of all variables defined for the model. Because the breeding program starts after cows are over two months in milk (standard voluntary waiting period of 60 days after calving), the months of pregnancy must be lower than the months in milk by at least two units

$$MC_{l,i+1,j} = (MC_{l,i,j})(1 - [CU_{l,m,i} / 100]) \text{ for all } l, j, \text{ and } m \tag{1}$$

$$MC_{l,i+1,j+1} = (MC_{l,i,j})(PG_{l,m,i}) \text{ for all } l, i = 2 - 12, \text{ and } m \tag{2}$$

$$MC_{l,i+1,0} = (MC_{l,i,0})(1 - [PG_{l,m,i} / 100]) \text{ for all } l \text{ and } m \tag{3}$$

($i \geq j + 2$). Combinations in which months in milk are not higher or equal to pregnancy months plus two are excluded from the model.

Chances for milking cows to become pregnant (PG) and to be culled (CU) at any specific time depend on local indices that are affected by parity, month of the year (m; 1 = January and 12 = December), and month in milk. Therefore, coefficients of milk production (MK) by milking cow group can be characterized by the stages defined with l, m, and i. For example, $CU_{2, 6, 8}$ denotes the culling rate for a group of second parity cows in the month of June with 8 months in milk. Indices used for model development in regard to pregnancy, culling, and milk production rates are described in the next section.

A series of integrated equations explain the dynamics of the milking cows and their production characteristics. First, the number of milking cows in any state and month are calculated by subtracting the culled animals using Equation 1.

Then, the number of pregnant (Equation 2) and non-pregnant (Equation 3) cows are calculated using the pregnancy rates. In typical dairy reproduction programs cows are targeted to conceive between 2 and 12 months in milk. A cow diagnosed as pregnant when 12 months in milk will calve during month 20, whereas a cow that is not pregnant by month 13 will be culled.

Dry cows and heifers are not described but are accounted similarly in the model. Dry cows gestate for 9 months and then move to the next parity. Heifers become pregnant between 12 and

23 months of age. The model assumes 50% of all newly born calves are female (Cabrera et al., 2006).

To start a simulation, the total number of adult cows in a herd is assigned to the cow state of first lactation, first month of milk, and non-pregnant ($CM_{1,1,0}$). Then, the simulation model distributes these cows and populates all possible cow states. Empirical trials of the model indicate that the model needs to run for 144 months (12 years) in order to populate all cow states. The model was consequently designed to run internally from month 1 to 144 maintaining the overall population of the herd. Then it continues running using the actual pregnancy and culling rates of the farm being modeled, displaying the results from the months 145 to 156, which is the 13th year (January to December).

New Mexico Indices
This study uses parameters found in the Dairy Herd Information Association (DHIA) records for New Mexico, compiled in 2006 by the processing centers of Raleigh, NC (www.drms.org), Provo, UT (www.dhiprovo.com), and Agri-Tech of Visalia, CA (www.agritech.com). Specific details on data collected through DHIA can be found at the Dairy Records Management System (www.drms.org/dhia.aspx). These records include monthly data from 23 dairy farms across New Mexico, which represents 14% of the dairy population of the state, including detailed information on number of cows, milk production, pregnancy rates, and culling rates. The averages of the monthly summaries were used as the seasonal indices for 1) pregnancy rates, 2) culling rates, and 3) first, second, and third and higher
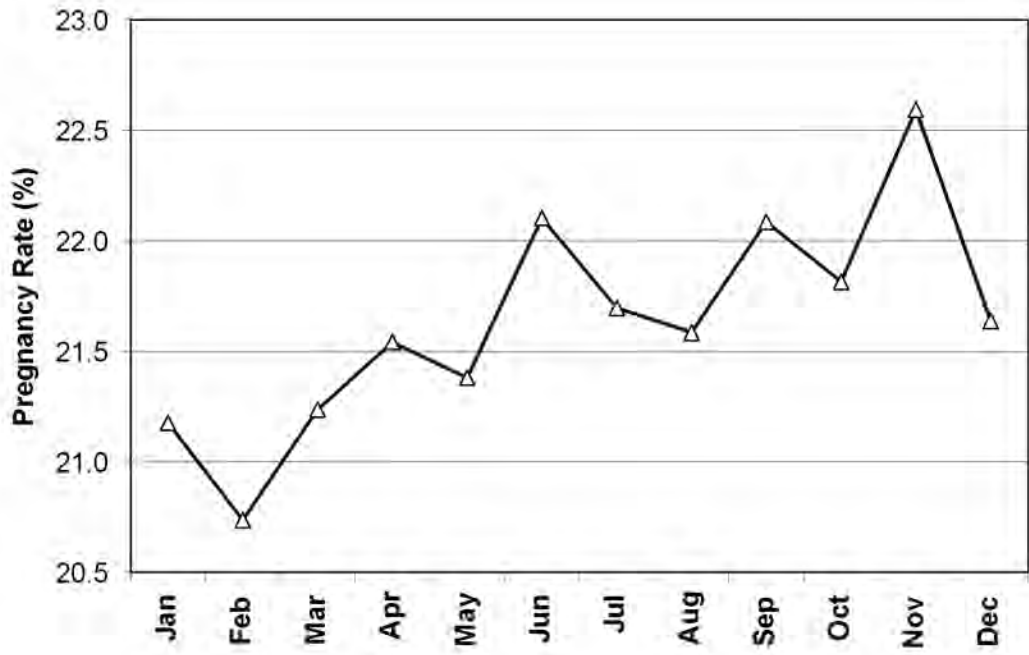
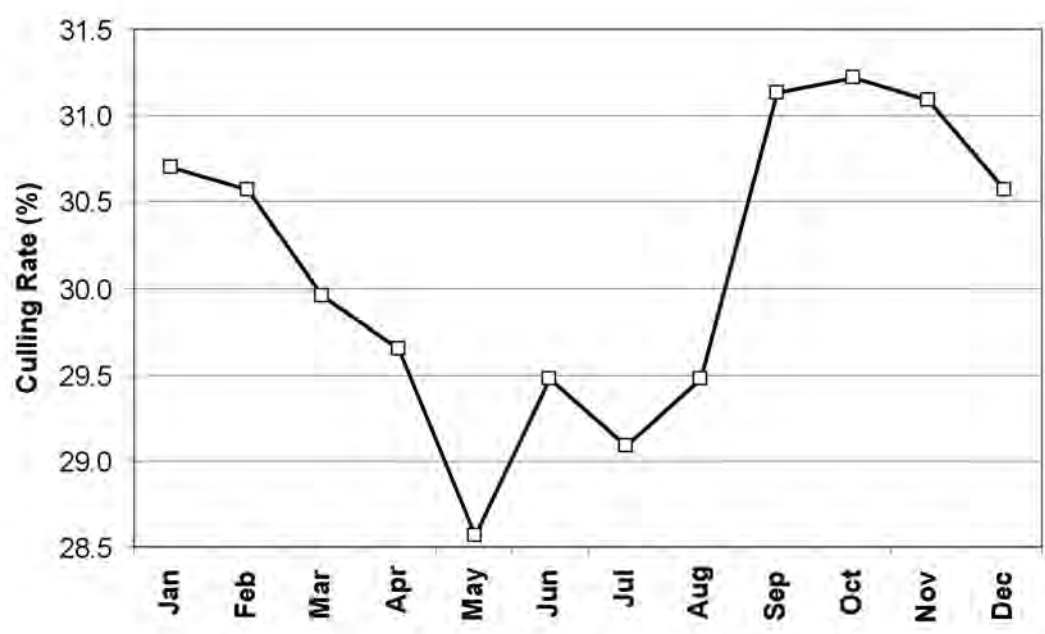*Figure 1A.* Pregnancy or conception rates in New Mexico by month.

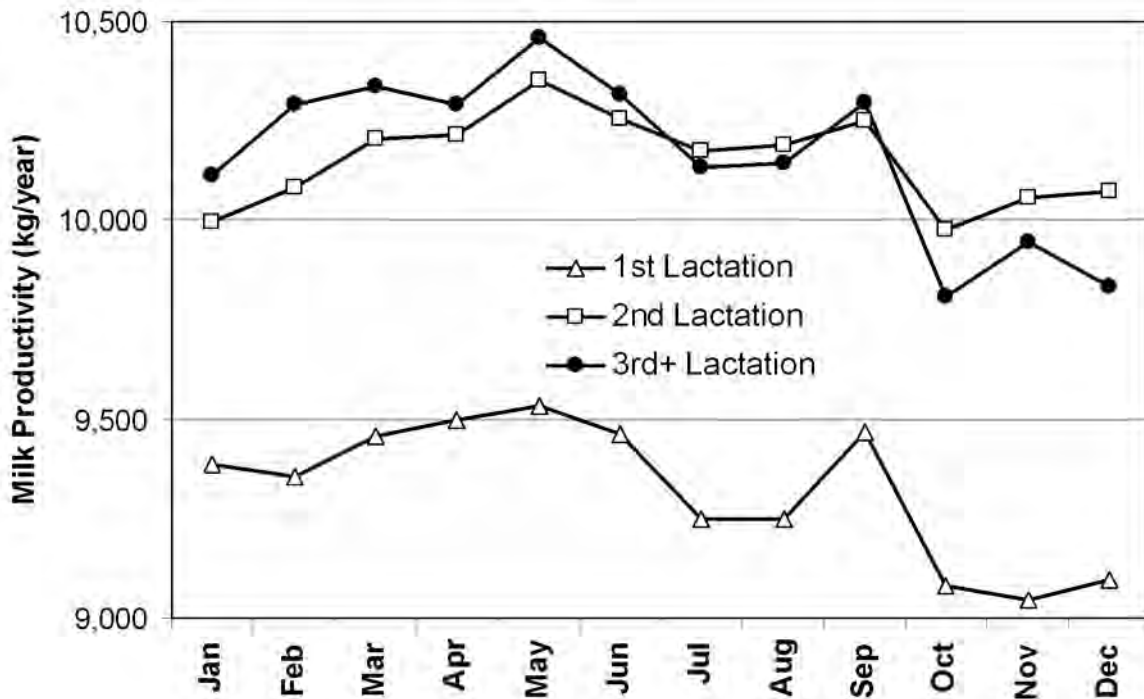*Figure 1B.* Yearly culling rates in New Mexico by month.

Figure 1C. **Milk productivity by lactation in New Mexico by month.**

lactation milk productivity. A three-dimensional matrix containing lactation, month of the year, and month in milk was used in Equation 1 ($CU_{l,m,i}$) to predict the number of culled animals and update the number of survivals.

These reports, however, do not have enough information to capture the interaction of these indices with respect to the cows' state in months in milk. Under the assumption that such correlation is universal, data from Cabrera et al. (2006) and deVries (2004) were used to include proportional variations (percentage of increase or decrease) relative to months in milk for pregnancy rates, culling rates, and milk productivity.

Pregnancy rates in New Mexico. Pregnancy rate is the percentage of successful conceptions during the 21-day estrus period of open cows. The overall average for New Mexico is 21.63% (min = 19.27%, max = 23.86%). Data indicate that the pregnancy rate is lower between January and May (lowest in February) and higher between June and December (highest in November; Figure 1A). These rates are assumed to remain constant across lactations (Cabrera et al., 2006).

Culling rates in New Mexico. Culling rate is the percentage of cows leaving the herd for any reason. The overall average culling rate for New Mexico dairies is 30.12% annually, or 2.51% monthly. Figure 1B shows the yearly culling rate by month. The culling rate increases in late summer and early fall (highest in October) and decreases during winter and spring (lowest in May). These rates are assumed to be constant across lactations (Cabrera et al., 2006).

Milk productivity in New Mexico. The overall rolling herd average (RHA) or average annual milk productivity per cow for the 23 herds in New Mexico for 2006 was 10,521 kg. Milk productivity increases across lactations. Milk productivity is least during the 1st lactation (10,232 kg), greater in 2nd lactation (11,142 kg), and slightly greater during the 3rd and higher lactations (11,155 kg). Seasonal trends in milk productivity were observed, with greater milk productivity in spring and early summer (greatest in May) and lower productivity in late fall and early winter (lowest in November; Figure 1C).

$$\text{MILK}_m = \sum_{l=1}^{9} \sum_{i=1}^{18} \sum_{j=0}^{7} (MC_{l,i,j})(MK_{l,m,i}) \quad \text{for } m = \text{any month} \tag{4}$$

If $\text{MILK}_m > 1.05 * \text{RHA}$ then $MK_{l,m,i} * F$, and

If $\text{MILK}_m < 1.05 * \text{RHA}$ then $MK_{l,m,i} / F$

$$\text{until} \sum_{m}^{11+m} \text{MILK}_m = RHA \pm 5\%(RHA)$$

where F is a factor proportional to the difference between MILK_m and RHA. $\tag{5}$

$$M_e = (MK)\, 0.616 + 46.25 \ (\text{kg}) \tag{6}$$

$$M_e = (MK)\,(0.726) + (0.66)\,(i) + 38.80 \ (\text{kg}) \tag{7}$$

A three-dimensional matrix containing lactation, month of the year, and month in milk ($MK_{l,m,i}$) is used to predict the total herd milk production for any month according to lactation stage and month in milk.

Prediction of Milk Production in New Mexico
Milk (MILK) is predicted by aggregating the amount of milk produced by every state of milking cow in every month, multiplied by the number of cows in such state (Equation 4).

In order to tailor site-specific predictions, milk productivity or RHA should be entered by the user instead of leaving the default to the average of 10,521 kg/cow/year. The RHA is a key parameter in the prediction of manure excretion and is a well-known parameter in any dairy farm. The model includes an algorithm that adjusts the milk production curves of all cow states to match the user-defined RHA within a 5% range of the entered value (Equation 5).

Prediction of Manure Excretion in New Mexico
Nennich et al. (2005) studied large datasets around the United States and found that, in ranked order, milk production and dry matter intake are better predictors of manure excretion by lactating cows than is body weight alone. These findings open a new set of opportunities for improving manure excretion predictions. Milk production is used as the main manure excretion predictor in the model because information on farm milk production is readily available for any dairy farm during any time period.

Results from Nennich et al. (2005) indicate that a milking cow daily excretes 0.616 kg of wet manure for every kilogram of milk produced, plus a constant manure excretion value of 46.25 kg (Equation 6).

This equation, however, does not include a factor that may reflect the changes in manure excretion according to month in milk. Using the same dataset, a new equation, including months in milk, was developed (Equation 7, T. D. Nennich [2006, personal communication]). This equation shows a

$$M_e{}^m = \sum_{l=1}^{9} \sum_{i=1}^{18} \sum_{j=0}^{7} \left(MC_{l,i,j}\right)\left(\left[MK_{l,m,i}\right]\left[0.33\right] + \left[0.66\right]\left[i\right] + 38.80\right)\left(DY_m\right)(\text{kg}) \text{ for } m = \text{any month} \quad (8)$$

$$M_e{}^d = \sum_{l=1}^{9} \sum_{i=12}^{20} \sum_{j=7}^{9} \left(MC_{l,i,j}\right)(38.05)\left(DY_m\right)(\text{kg}) \text{ for } m = \text{any month} \quad (9)$$

$$M_e{}^{farm} = M_e{}^m + M_e{}^d (\text{kg}) \text{ in any month} \quad (10)$$

daily increase of 0.66 kg of wet manure for every increase in month in milk and an increase of 0.33 kg of wet manure for every 0.45 kg of milk produced, plus a constant manure excretion value of 38.80 kg.

Equation 8 was integrated with Equations 1 to 5 to predict manure excretion at the farm level by using milk production and cow state as main predictors. Equation 8 predicts manure excretion by an individual dairy farm during any month. A specific dairy farm is defined by the parameters *number of adult cows, RHA, pregnancy rate,* and *culling rate,* where DY_m is the number of days in month m.

In addition, between 6% and 15% of adult cows are in a dry state (not producing milk) at any time, and have a different rate of manure excretion than lactating cows. Therefore, the model used the AS-ABE (2005) standards that indicate that a dry cow produces 38.05 kg of wet manure in a day (Equation 9).

The overall manure excreted on a dairy farm in a month is calculated by adding Equations 8 and 9 (Equation 10).

Outcomes from the model are compared through Sensitivity Analyses (Johnson et al., 2007) regarding 1) pregnancy rates, 2) culling rates, and 3) milk productivity for New Mexico conditions, and are summarized and aggregated by counties across the state.

RESULTS AND DISCUSSION

Manure Excretion for an Average Dairy in New Mexico

The model predicted the production of 45,812 MT of wet manure per year for an average dairy farm in New Mexico that has 2,000 adult cows and average DHIA indices for RHA or milk productivity (10,521 kg/cow/year), pregnancy rate (21.63%), and culling rate (30.12%). Ninety-three percent of this excretion was predicted to be from the milking cows, whereas the remaining 7% was from the dry cows.

These manure excretion predictions have strong seasonal variations throughout the year. Excretions are lower during September through December, medium during January through March and in August, and higher between April and July (Figure 2A). The variation in manure excretion throughout ranges from 3,510 to 3,928 MT/month (Figure 2B).

Van Horn et al. (2003) proposed an average 63 kg of daily excretion for dairy cattle, which was based upon averaging high-, medium-, and low-production cows with dry cows. The most recent standards indicate that lactating cows produce 68 kg and dry cows 38 kg of manure daily (ASABE, 2005), resulting in an average of approximately 66 kg of wet manure per cow per day. Using these approaches, overall dairy farm manure excretion is assumed to be constant throughout the year and
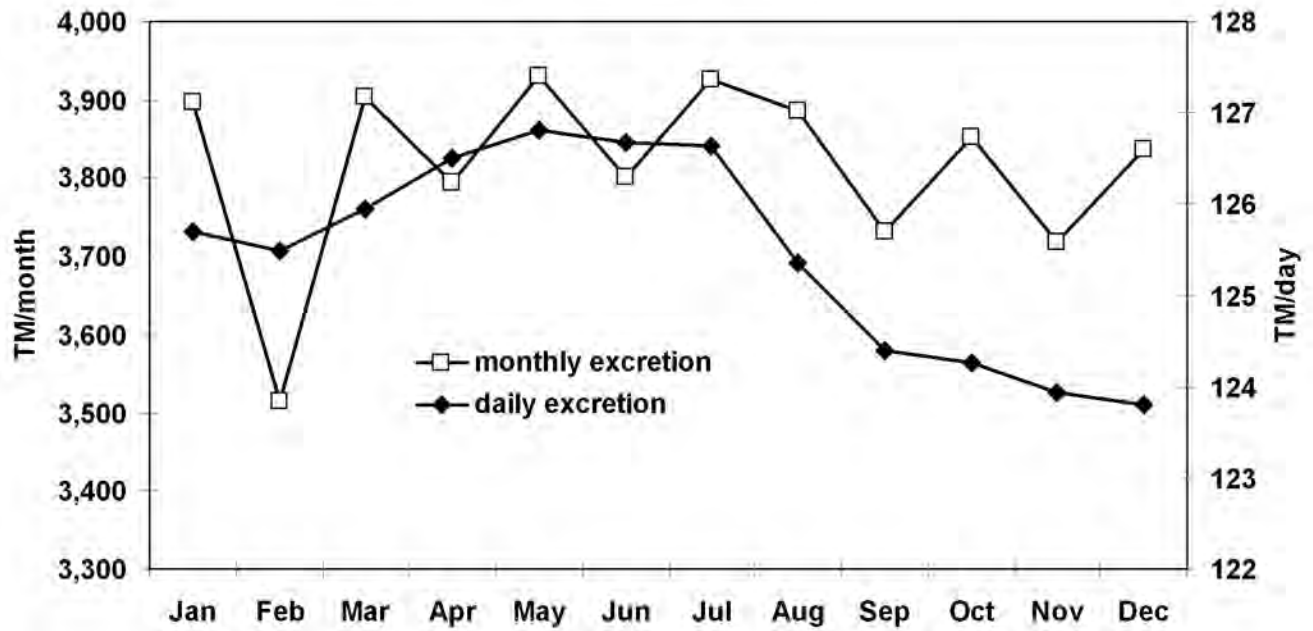
Figure 2A. Manure excretion prediction in a 2,000-cow New Mexico dairy farm.
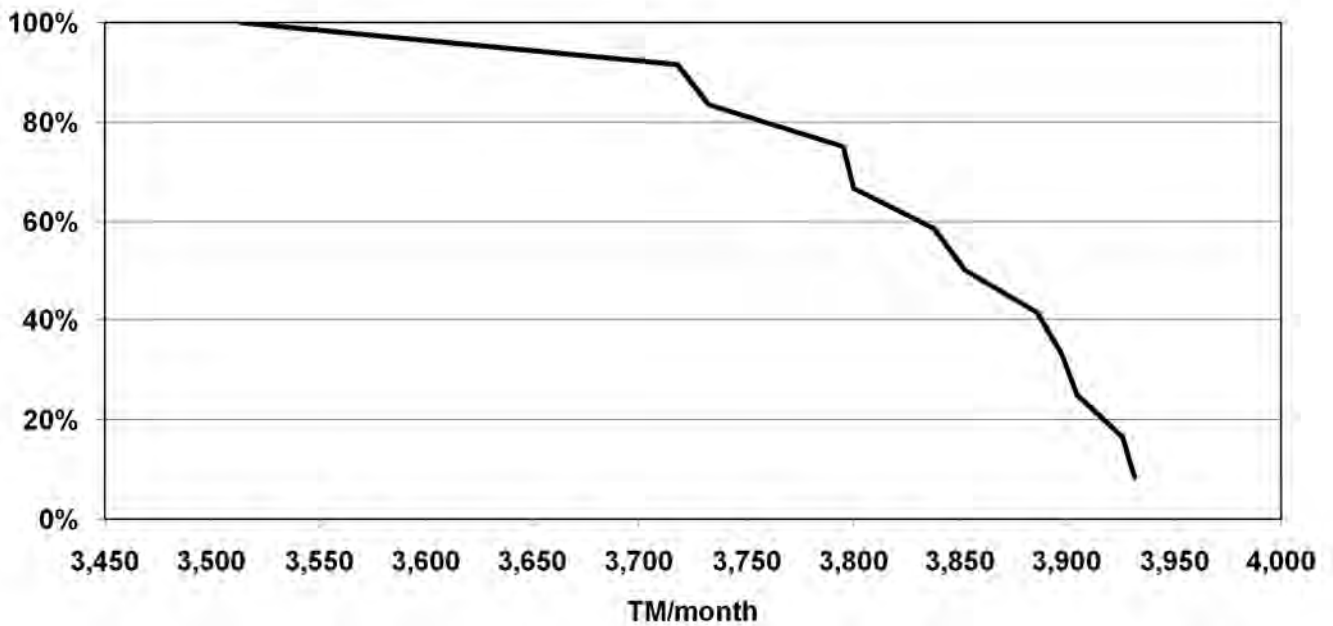

Figure 2B. Probability of exceedance in a 2,000-cow New Mexico dairy farm.

consequently is estimated by multiplying the daily average excretion per cow by the number of cows in a herd.

Overall model predictions averaged 63 kg/cow/day, not substantially different from Van Horn et al. (2003) or ASABE (2005) estimates: 4% lower than those proposed by the ASABE and virtually the same as those used by Van Horn et al. However, our model differs from the earlier approaches by providing seasonal estimates by tailoring dairy farm specific parameters such as milk productivity, pregnancy rates, and culling rates.

Milk production exhibits seasonal fluctuations. The "spring flush" is well documented, with milk production levels that can be as much as 20% greater than the yearly average (Cabrera & Hagevoort, 2007). Similarly, hot summers and cold winters can decrease milk production by similar amounts. This seasonality or environmental effect is not exclusive to milk production, but also impacts reproductive performance, health or disease outbreaks, feed and water consumption, and manure excretion (Nennich et al., 2003; Jonker et al., 2002).

Sensitivity of Manure Excretion to Milk Productivity (RHA)

Milk productivity (RHA) in the 2006 New Mexico dairy records varied between 9,500 and 11,181 kg/cow/year. Using average parameters for culling rates (30.12%) and pregnancy rates (21.63%), the variation in manure excretion was evaluated with respect to variations in the RHA. As expected, the excretion of manure varies in direct relation to the RHA. More specifically, for a 17.70% increase in RHA (9,500 to 11,182 kg/year), manure excretion increased 5.48% (44,317 to 46,746 MT/year) (Figure 3A). Seasonal variation of manure excretion within year for differing rates of milk productivity and defined culling and pregnancy rates were also directly related to RHA.

Sensitivity of Manure Excretion to Pregnancy Rate

The observed pregnancy rate in the DHIA New Mexico records for 2006 varied from 19.23% to 23.86%. Using the average RHA of 10,521 kg/cow/year and the culling rate of 30.12%, the model predicted manure excretion for different pregnancy rates for a typical 2,000-cow dairy operation in New Mexico (Figure 3B). As expected, higher pregnancy rates lead to more lactating females and therefore greater predicted manure excretion. However, this impact is not static, because in months like February and September the excretion would be very similar for different pregnancy rates, whereas it would have larger variation in months like July and December.

Sensitivity of Manure Excretion to Culling Rate

The observed annual culling rate in the DHIA New Mexico records for 2006 varied from 27.2% to 35.0%. Using the New Mexico DHIA average RHA of 10,521 kg/cow/year and pregnancy rate of 21.63%, the model predicted higher amounts of manure excretion for lower culling rates (Figure 3C). As expected, lower culling rates result in more animals remaining in the herd. At a steady pregnancy rate, lower culling rates determine size expansion and consequently higher amounts of manure excreted. In Figure 3C the difference in manure excretion due to different culling rates increases over time because culling animals at a certain rate will have a cumulative effect on how many animals are carried over from one month to the next.

Manure Excretion by Counties and Geographic Regions in New Mexico

Assuming the DHIA average data for New Mexico RHA of 10,521 kg/cow/year, pregnancy rate of 21.63%, and culling rate of 30.67%, manure excretion by county in New Mexico was predicted using statistical data of geographic dairy cattle distribution in the state (NASS, 2007). Table 2 shows predicted manure excretion, by month, in New Mexico counties where dairy farms are located.

Dairy cows in New Mexico produce 7.7 million MT of wet manure per year, which is equivalent to 1.0 million MT of dry manure. Thus, there is an opportunity and a need for the monthly use of 84,116 MT of dairy manure, with seasonal ranges from 77,584 MT (February) to 86,689 MT (May). Manure excretion is concentrated in the top milk-producing counties of Chaves (20,537 to 22,947 MT/month), Curry (15,060 to 16,828 MT/month), Roosevelt (14,832 to 16,572 MT/month), and Doña Ana (12,094 to 13,513 MT/month).
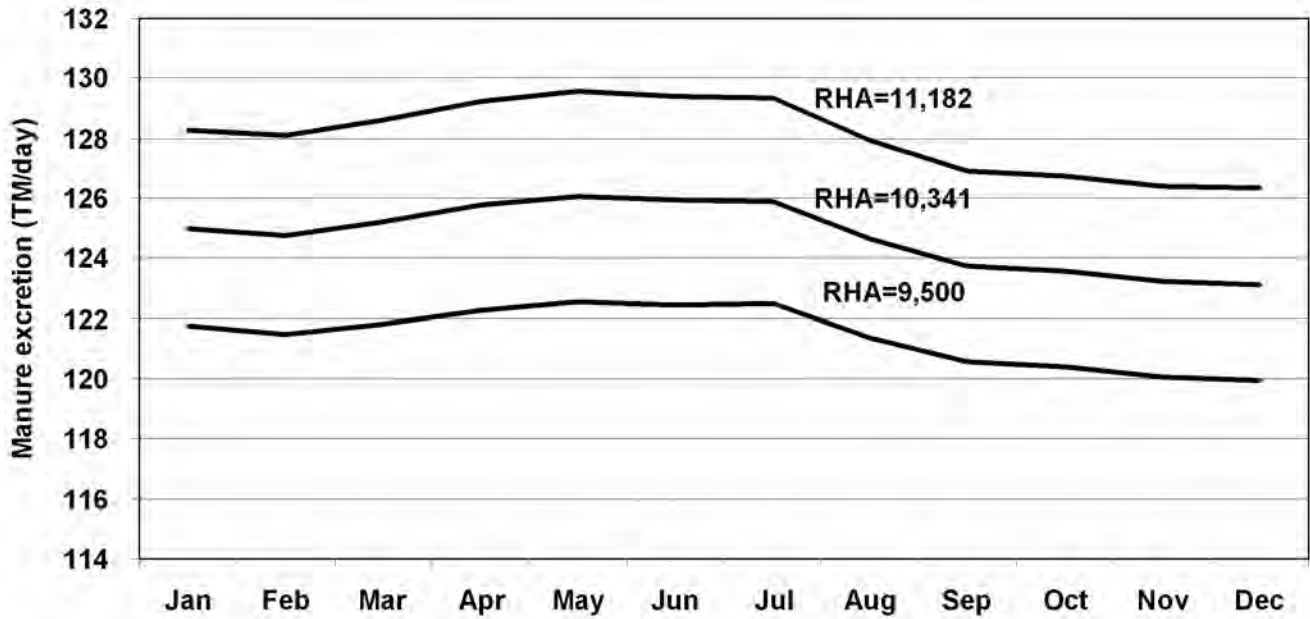
Figure 3A. Manure excretion at different milk productivity rates (RHA in kg/cow/year).
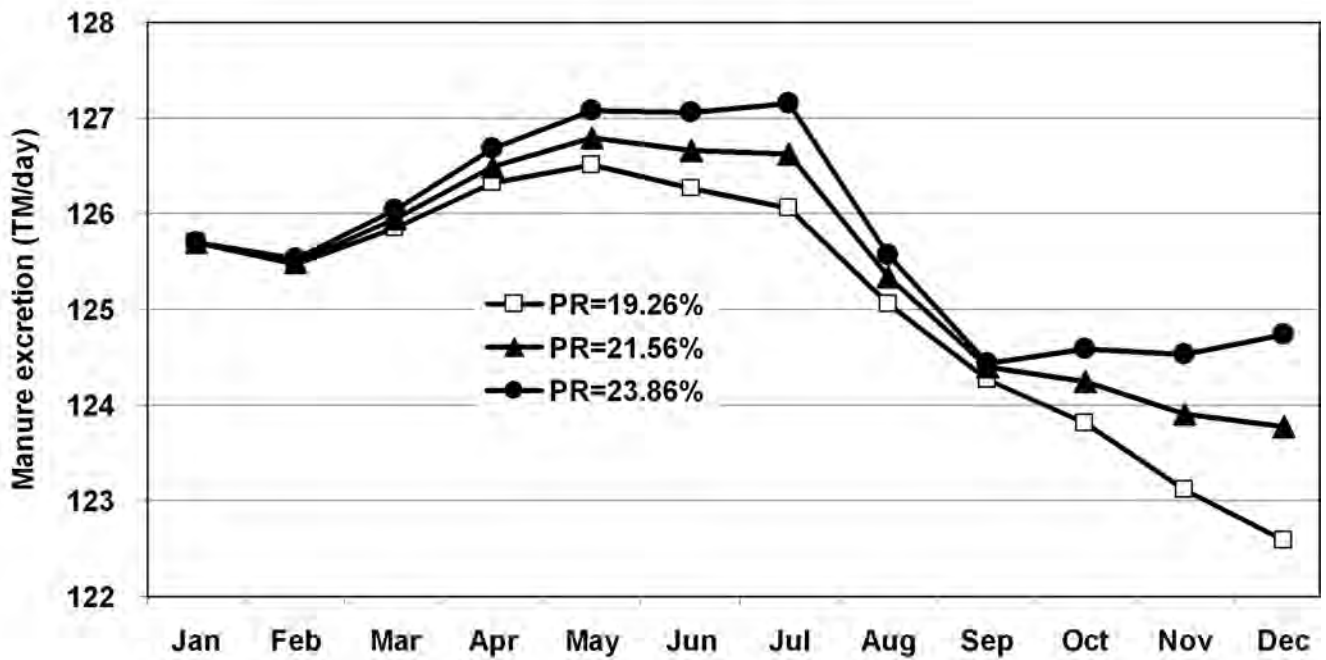

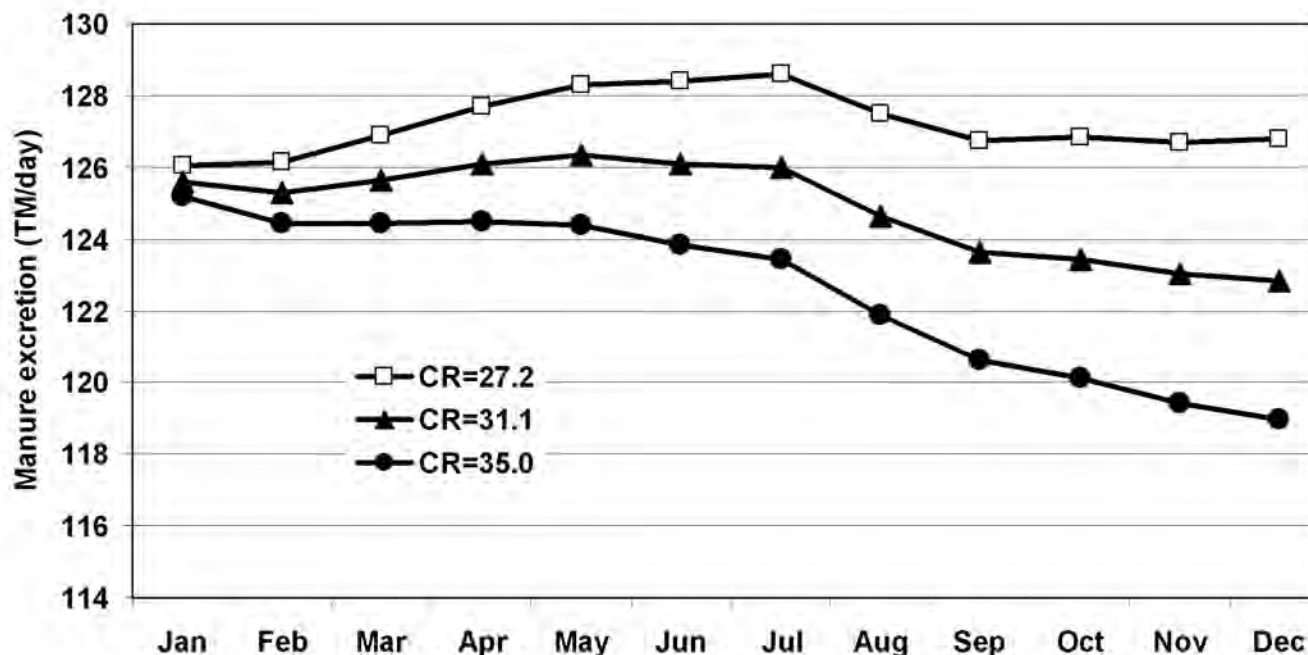*Figure 3B.* Manure excretion at different pregnancy rates.

Figure 3C. Manure excretion at different culling rates.

Table 2. Predicted Manure Excretion (MT) by Dairy Cattle in New Mexico

	Chaves	Curry	Roosevelt	Doña Ana	Lea	Eddy	Others[2]	New Mexico Wet Manure	New Mexico Dry Manure[3]
# Cows[1]	90,000	66,000	65,000	53,000	25,000	19,000	22,000	340,000	340,000
				Tons of Manure Excreted					
January	175,274	128,534	126,587	103,217	48,687	37,003	42,845	662,146	86,079
February	157,976	115,850	114,094	93,030	43,882	33,350	38,617	596,799	77,584
March	175,450	128,663	126,713	103,320	48,736	37,039	42,888	662,810	86,165
April	170,467	125,010	123,115	100,386	47,352	35,987	41,670	643,988	83,719
May	176,515	129,445	127,483	103,948	49,032	37,265	43,148	666,836	86,689
June	170,583	125,094	123,199	100,455	47,385	36,012	41,698	644,425	83,776
July	176,162	129,185	127,228	103,739	48,934	37,190	43,062	665,499	86,515
August	174,311	127,828	125,891	102,650	48,420	36,799	42,609	658,508	85,606
September	167,359	122,730	120,870	98,556	46,488	35,332	40,910	632,244	82,192
October	172,689	126,639	124,720	101,695	47,969	36,457	42,213	652,380	84,810
November	166,606	122,178	120,327	98,112	46,280	35,173	40,726	629,400	81,822
December	171,929	126,081	124,170	101,246	47,757	36,296	42,027	649,507	84,436
Total (year)	2,055,321	1,507,235	1,484,398	1,210,356	570,923	433,901	502,411	7,764,543	1,009,390
Total (year) dry[3]	267,191	195,940	192,972	157,346	74,220	56,408	65,313	_____	_____

[1]2006 statistics, NASS (2007).

[2]Sierra, Valencia, Bernalillo, Torrance, and Luna counties.

[3]13% manure dry matter basis, ASABE (2005).

IMPLICATIONS

Prediction of the seasonal variation in dairy manure excretion is a substantial improvement over previous approaches, creates better opportunities for calculating manure recycling needs, and aids in addressing issues related to bioenergy production, manure management, and assessment of environmental impacts. The predictions generated by the developed model are consistent with local and national predictions. These total calculations are also consistent with estimates generated using DMI baselines. Nonetheless, the model could likely be improved by collecting and including local experimental data to parameterize regional prediction equations of manure excretion. The stochastic herd dynamic simulation model is considered a baseline model. Other modules can be developed and interfaced, providing ample possibilities to study dairy farm systems along with increased input from producers. Until the model is fully validated, caution is advised when using results of the model outside the parameters of the DHIA records for milk productivity, pregnancy rates, and culling rates that were used in the model development.

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