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NM-Manure: A Seasonal Prediction Model of Manure Excretion for Lactating Dairy Cows in New Mexico

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Abstract. *Environmental concerns from dairy farms arise primarily because of the potential negative impacts of manure and urine excretions by dairy cattle on air, soil, and water resources. In addition, increasing opportunities are arising for using manure as a source of renewable energy. Consequently, it is important to assess the amounts of manure excreted by dairy herds. Regulatory agencies use only a few animal groups and average herd characteristics to estimate steady manure excretion. However, manure excretion varies seasonally and should be predicted based on dynamic herd group characteristics. Prediction parameters are periodically revised and improved by regulatory agencies. This study describes the creation of a stochastic dynamic herd model to predict seasonal manure excretion that matches current regulatory standards by adjusting improved predictor parameters. The Markov-chain model defines more than 1,400 cow states according to parity, month in milk, and pregnancy; and includes season of the year according to New Mexico pregnancy and culling rates. This model uses a well-known parameter of milk rolling herd average to estimate milk productivity by any cow in the herd to predict manure excretion in any month. Results indicated strong seasonal variations of manure excretion.*

Keywords. Markov-chain, dynamic stochastic simulation, herd dynamic simulation, environmental impacts.

Introduction

Environmental concerns from dairy farms arise primarily because of the potential negative impacts of manure and urine excretions by dairy cattle on air, soil, and water resources. Manure excretion is unavoidable and an intrinsic part of any dairy farm production system. The specific amounts of manure excreted, however, vary substantially and are not well understood. Calculated amounts of manure excretion, for regulation purposes, are estimated using standard parameters and average herd characteristics. However, parameters are periodically revised and new models are being developed to better understand herd dynamics and manure excretion characteristics.

Every cow is a unique and performs biologically independently according to its genetic make-up and environmental stimuli. Ideally, manure produced by each cow in a dairy herd would be integrated at the herd level to improve estimates of the amounts of manure excreted for a specific farm during a specific period of time. Accomplishing this task is not technically or economically feasible. However, an intermediate approach using simulation modeling is possible, and would provide more realistic estimation of manure excretions. A simulation approach predicting seasonal changes in manure excretion would be a substantial improvement over the approach currently used in New Mexico that assumes excretion to be steady over time for all cows regardless season of the year and herd dynamics.

Dairy farming is a non-stop agricultural production activity that exhibits seasonal patterns of milk production. The “spring flush” is well documented in the mid-West with up to 20% more than normal milk production (Cabrera & Hagevoort, 2006). Similarly, very hot summers and very cold winters decrease milk production by similar amounts. This seasonality or environmental effect on dairy performance is not exclusive to milk production, but also impacts reproductive performance, health or disease outbreaks, feed and water consumption, and manure excretion.

An understanding of the seasonality of manure excretion is important for determining opportunities for manure recycling and use, and is related to spatial and temporal environmental impacts. For example, higher amounts of manure can be applied to crop fields during spring-summer when plants are actively growing, amount of renewable energy produced would decrease towards late summer when less manure would be excreted, and higher risks of air pollution may exist when dry and windy conditions persist. Also, seasonality of manure excretion is important for opportunities of using it as renewable source of energy.

More accurate estimates of manure excretion are also needed for manure storage and nutrient management plans. Estimates of manure excretion for New Mexico are currently based on recommendations (Sporcic et al., 2006) of the Natural Resources and Conservation Service (USDA-NRCS). These recommendations assume 80 lbs/day (36.32 kg/day) of wet manure are excreted for every 1,000 lbs (454 kg) of live bodyweight, and are based upon the national standards published by the Agricultural Waste Management Field Handbook (USDA, 1992). In order to calculate these estimates, Sporcic et al. (2006) assumes an average standard body weight of 1,400 lbs (635.6 kg) for all lactating cows in the herd. Using this approach, wet manure excretion is estimated to be 112 lbs (51 kg) for every lactating cow is assumed to be constant throughout the year. According to the most recent standards published by ASABE, lactating cows produce 68 kg (150 lbs) and dry cows 38 kg (84lbs) of manure daily (ASABE, 2005).

Better prediction equations are available and are being used in other states and regions. For example, Weiss (2004) presented equations of manure prediction based on dry matter intake (DMI) and milk production from 232 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.

Studies, data, and parameterization as performed by Weiss (2004) and Nennich et al. (2005) are major advancements to current standards (USDA, 1992; ASABE, 1999, 2005) and provide increased accuracy in manure prediction. This opens the possibility for the use of improved predictors in other areas and regions. There are no known studies performed in New Mexico at the animal or farm simulation level.

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

Materials and Methods

This study integrates a newly created simulation model of herd dynamics for New Mexico following Cabrera et al. (2006) with the current parameterizations of manure excretion (Nennich et al., 2005) to predict manure excretion at the farm level based on the cow production stage and seasonality.

Stochastic simulation of milking cow dynamics

A Markov-chain approach (deVries, 2004; St-Pierre and Thraen, 1999) simulates the dynamics of the dairy herd by calculating the number of cows (MC) in each of more than 1,400 to-be-defined cow production stages, by month. From these variables, it calculates manure excretion. A cow state or production stage is characterized by three dimensions: *l* is lactation or parity (1 to 9), *i* is the month in milk (1 to 20), and *j* is month of pregnancy (unbred or up to 9 months pregnant, 0 to 9). For example, $MC_{2, 10, 5}$ denotes a group of cows of second lactation with 10 months in milk and five months pregnant. Because the breeding program starts after cows are over two months in milk (standard voluntary waiting period of 60 days after delivery), the months of pregnancy must be lower than the months in milk by at least two units ($i \geq j+2$). Combinations in which months in milk are not higher or equal to pregnancy months plus two are excluded from the model. Table 1 contains a list of all variables defined for the model.

Chances for milking cows to become pregnant (PG) and to be culled (CU) at any specific point in time depend on local indexes that are affected by parity (*l*), month of the year (*m*), and month in milk (*i*). Month of the year (*m*) is defined such that 1=January and 12=December. In similar fashion, 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 milking cow group of second parity, in the month of June, with 8 months in milk. Indices for New Mexico in regard to pregnancy, culling, and milk production rates are described in next section.

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

$MC_{l,i+1,j}=(MC_{l,i,j})(1-CU_{l,m,i})$ for all *l, j*, and *m* [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 cow between the months of milk 2 to 12. A cow pregnant in month 12 will calve during month 20, while a cow that is not pregnant by month 13 will be culled.

$MC_{l,i+1,j+1}=(MC_{l,i,j})(PG_{l,m,i})$ for all *l*, *i*=2-12, and *m* [2]

$MC_{l,i+1,0}=(MC_{l,i,0})(1-PG_{l,m,i})$ for all *l* and *m* [3]

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. The model assumes 50% of all newly born calves are female.

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. During this run, controlling pregnancy and culling rates to maintain the size of the herd population is critical. The model was consequently designed to run internally from month 1 to 144 maintaining the overall population of the herd. It then continues running and displaying the results from the months 145 to 156, which is a year (January to December) using the actual pregnancy and culling rates of the farm being modeled.

Table 1. Variables of the NM-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)	manure excreted by dairy cattle
M_e^d (kg)	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
$MK_{i,m,k}$ (kg day^{-1})	milk production for cows in *i* months in milk, during *m* month of the year, and in *k* lactation
$MILK_m$ (kg)	herd milk production
RHA (kg yr^{-1})	rolling herd average, 12-months 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

*Unless otherwise stated

New Mexico indexes

This study uses parameters found in the Dairy Herd Improvement Association (DHIA) records for New Mexico, compiled in 2006 by the processing centers of Raleigh, NC (http://www.drms.org/), Provo, UT (http://www.dhiprovo.com/), and Agri-Tech of Visalia, CA (http://www.agritech.com/). Specific details on data collected through DHIA can be found at the Dairy Records Management System (http://www.drms.org/dhia.htm). These records include monthly data from 23 dairy farms across New Mexico including detailed information of number of cows, milk production, pregnancy rates, and culling rates. The averages of the monthly summaries were used as the seasonal indexes for: 1) pregnancy rates, 2) culling rates and 3) first, second, and third and higher lactation milk productivity.

These reports, however, do not have enough information to capture the interaction of these indexes with respect to 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.

The data used from these 23 dairy farms (13.4% of the dairy population in New Mexico) are a "purposeful" sample of New Mexico dairy herds, but may or may not represent the characteristics of the entire population. The modeling structure employed allows users to extrapolate these parameters to represent specific dairy conditions in New Mexico, but results may not be as good as those inside the parameters found in the DHIA records.

Pregnancy rates in New Mexico

Pregnancy rate is the monthly percentage (%) of success conception by cows between the second and twelfth month in milk. 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; Fig. 1A). These rates are assumed to remain across lactations (Cabrera et al., 2006).

A three dimensional matrix containing: lactation, month of the year, and month in milk was used in Equations 2 and 3 ($PG_{l,m,i}$) to predict the number of unbred and pregnant cows and the calving activity at any time in the herd.

Culling rates in New Mexico

Culling rate is the percentage (%) or number 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. Fig. 1B shows the yearly culling rate by month. The culling rate increases in late summer and early fall (highest is October) and decreases during winter and spring (lowest is May). These rates are assumed to be constant across lactations (Cabrera et al., 2006).

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.

Milk productivity in New Mexico

The overall rolling herd average (RHA) or average milk productivity per cow for the 23 herds in New Mexico for 2006 was 23,147 lbs (10,509 kg). Milk productivity increases across lactations; the lowest productivity occurred for the 1^{st} lactation (22,538 lbs or 10,232 kg), which increased in 2^{nd} lactation (24,542 lbs or 11,142 kg) and was the highest for 3^{rd} and higher lactations (24,570 lbs or 11,155 kg). Overall, higher milk productivity is observed in spring and early summer (highest in May) and lower productivity is observed in late fall and early winter (lowest in November; Fig. 1C).

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).

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

In order to tailor site specificity with the predictions, milk productivity or RHA should be entered by the user instead of leaving the default to the average of 23,147 lbs/cow/year. The RHA is a key parameter in the prediction of manure excretion and this 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 inputted RHA of a herd, within a 5% of precision, Equation 5.

If $MILK_m > 1.05 * RHA$ then $MK_{l,m,i} * F$, and

If $MILK_m < 1.05 * RHA$ then $MK_{l,m,i} / F$ [5]

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

where F is a factor proportional to the difference between $MILK_m$ and RHA.

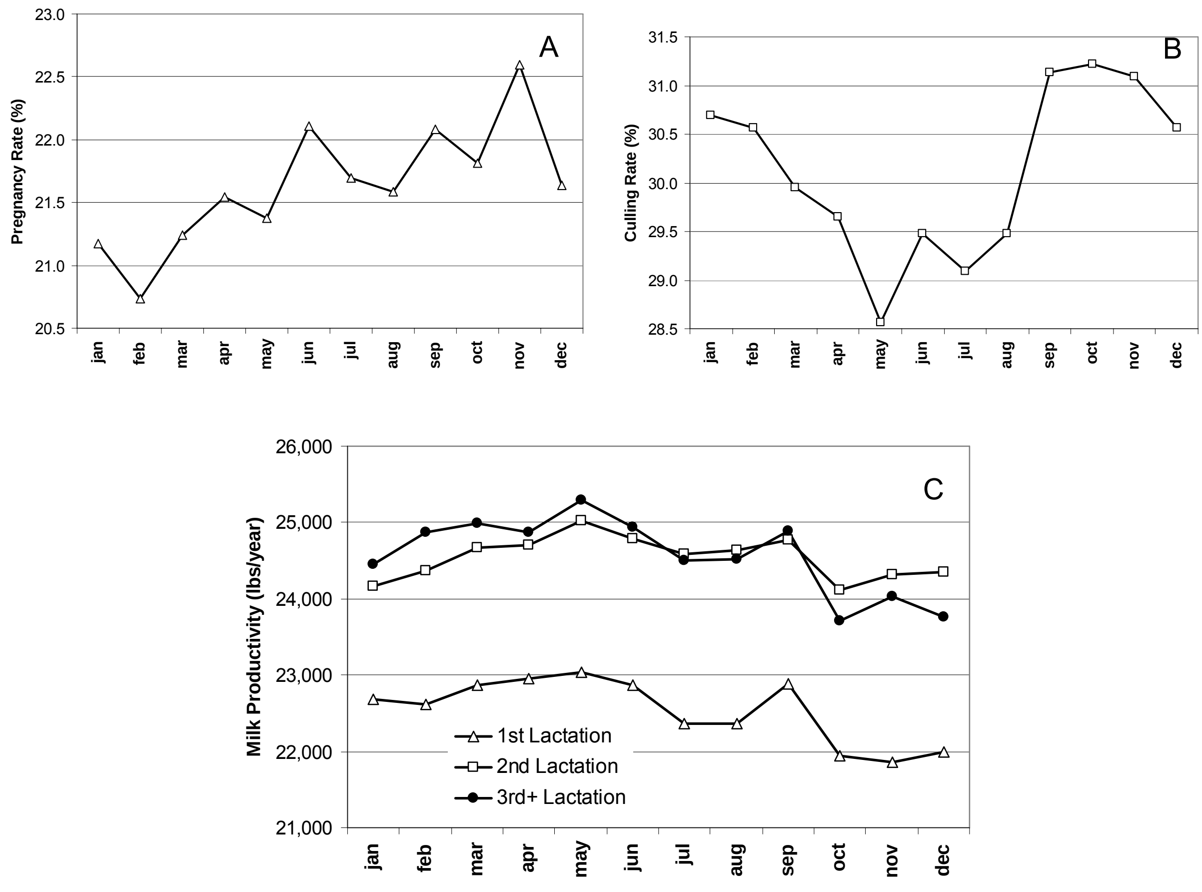

Figure 1. Pregnancy rates (A), yearly culling rates (B), and milk productivity by lactation (C) in New Mexico by month.

Prediction of manure excretion in New Mexico

Currently, New Mexico estimates assumes that a lactating cow produces 112 lbs (50.85 kg) of manure (M_e) or 80 lbs (36.32 kg) of manure by every 1,000 lbs (454 kg) of animal live weight (LW), which is considered to be 1,400 lbs (635.60) (Sporcic et al., 2006), Equation 6.

$M_e = (LW)(80/1{,}000)$ (lbs) [6]

However, 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 excretes 0.616 pounds of manure for every pound of milk produced, above a constant of 101.76 pounds, Equation 7.

M_e = (MK) (0.616 ± 0.057) + 101.76 ± 5.07 (lbs) [7]

This equation, however, does not include a factor that may reflect the changes in manure excretion because excretion by month in milk. Using the same dataset, a new equation including months in milk, *i*, was developed (Equation 8; Nennich, T.D., personal communication) and shows an increase of 1.45 lbs of manure for every increase in month of milk and 0.72 lbs of additional manure for every additional pound of milk over 85.37 lbs.

M_e = (MK) (0.72) + (1.45) (*i*) + 85.37 (lbs) [8]

Finally, Equation 9 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 9 predicts manure excretion by an individual dairy farm in New Mexico during any month. A specific dairy farm is defined by the parameters: number of adult cows, RHA, pregnancy rate, and culling rate.

$$M_e^m = \sum_{l=1}^{9} \sum_{i=1}^{18} \sum_{j=0}^{7} (MC_{l,i,j})(i*1.45 + 0.42*MK_{l,m.i} + 85.37)(DY_m) \text{ (lbs)}$$

for *m*=any month [9]

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 ASABE (2006) standards that indicate that dry cows produce 83.7 lbs (38 kg) of manure in a day were used (Equation 10).

$$M_e^d = \sum_{l=1}^{9} \sum_{i=12}^{20} \sum_{j=7}^{9} (MC_{l,i,j})(83.7)(DY_m) \text{ (lbs) for } m\text{=any month} \quad [10]$$

The overall manure excreted in a dairy farm in a month is calculated by adding Equations 9 and 10 (Equation 11).

$M_e^{farm} = M_e^m + M_e^d$ (lbs) in any month [11]

Results

Manure excretion for an average dairy in New Mexico

The model predicted the production of 50,500 tons of wet manure per year for an average dairy farm in New Mexico that has 2000 adult cows and the average DHIA indexes for RHA or milk productivity (23,147 lbs/cow/year), pregnancy rate (21.63%), and culling rate (30.12%). Ninety-three percent of this excretion was accounted to be from the milking cows, while the remaining 7% came 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 (Fig. 2A). The variation in manure excretion throughout ranges from 3,870 to 4,330 tons/month (Fig. 2B).

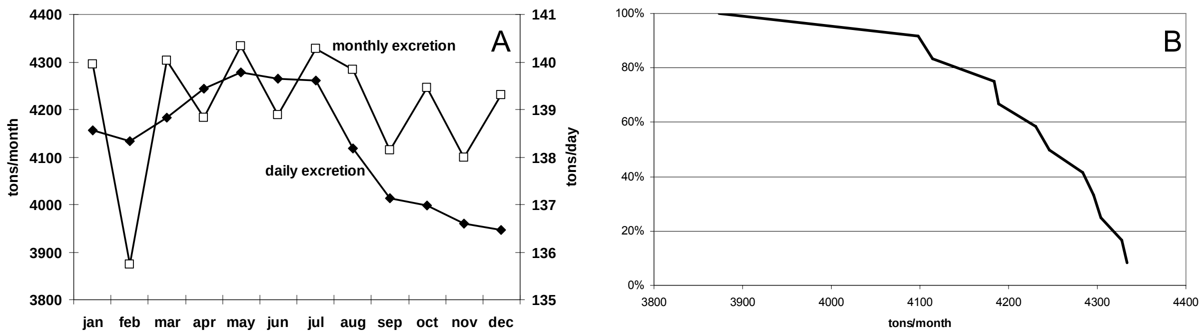

Figure 2. Manure excretion prediction (A) and probability of exceedance (B) in a 2000-cow New Mexico dairy farm.

Sensitivity of manure excretion to milk productivity (RHA)

Milk productivity (RHA) in the 2006 New Mexico dairy records varied between 20,900 and 24,600 lbs/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, but in lower proportion: for an increase in RHA of 17.70% (20,900 to 24,600 lbs/year) the manure excretion increased 5.48% (48, 852 to 51,529 tons/year; Fig. 3A). The seasonal variation of manure excretion across the year for different rates of milk productivity, for defined culling and pregnancy rates follows the same pattern.

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 23,147 lbs/cow/year and the culling rate of 30.12%, the model predicted manure excretion for different pregnancy rates for a typical 2000-cow dairy operation in New Mexico (Fig. 3B). As expected, higher pregnancy rates leads to more lactating females and therefore greater predicted manure excretion. However, this impact is not monotonic 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 culling rate in the DHIA New Mexico records for 2006 varied from 27.2 to 35.0 %. Using the DHIA average values for New Mexico of RHA of 23,147 lbs/cow/year and pregnancy rate of 21.63%, the model predicted higher amounts of manure excretion for lower culling rates (Fig. 3C). As expected, lower culling rates determine more animals remaining in the herd (herd size expansion) and consequently higher amounts of manure excreted. In Fig. 3C the difference in manure excretion due to different culling rates increases over time because there will be an accumulated effect of culling animals determining more or less animals carried over from one month to the next.

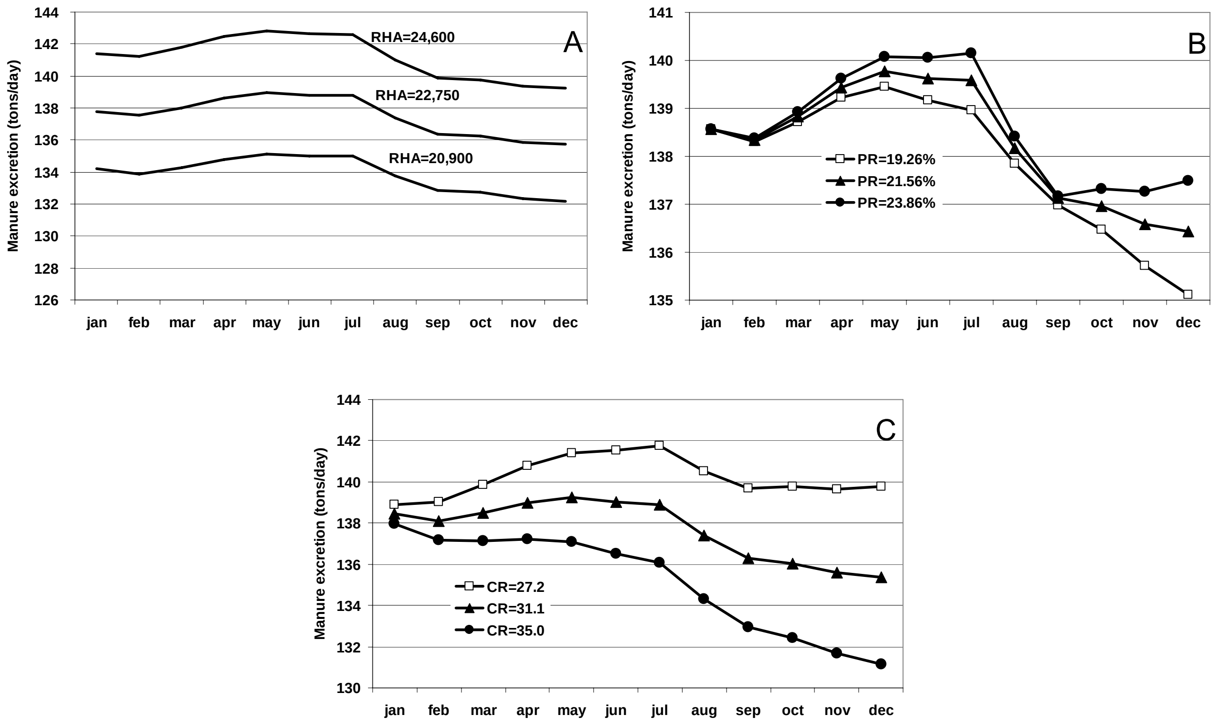

Figure 3.Manure excretion at different milk productivity rates (RHA in lbs/cow/year) (A), at different pregnancy rates (B), and at different culling rates (C).

Manure excretion by counties and geographic regions in New Mexico

Assuming the DHIA average data for New Mexico of RHA (23,147 lbs/cow/year), pregnancy rate (21.63%) and the culling rate (30.67%), and statistical data of geographic dairy cattle distribution in the state (NASS, 2007); the amount of manure excretion by county in the state of New Mexico was assessed. Table 2 shows predicted manure excretion by month in New Mexico counties where dairy farms are located.

Table 2. Seasonal manure excretion prediction (tons) by dairy cattle in New Mexico.

	Chaves	Curry	Roosevelt	Doña Ana	Lea	Eddy	Others*	New Mexico Wet Manure	New Mexico Dry Manure**
# Cows* **	**90,000**	**66,000**	**65,000**	**53,000**	**25,000**	**19,000**	**22,000**	**340,000**	**340,000**
January	193,204	141,683	139,537	113,776	53,668	40,788	47,228	729,883	94,885
February	174,137	127,701	125,766	102,547	48,371	36,762	42,567	657,851	85,521
March	193,398	141,825	139,676	113,890	53,722	40,828	47,275	730,615	94,980
April	187,906	137,798	135,710	110,656	52,196	39,669	45,933	709,868	92,283
May	194,573	142,687	140,525	114,582	54,048	41,077	47,562	735,053	95,557
June	188,034	137,891	135,802	110,731	52,232	39,696	45,964	710,350	92,346
July	194,183	142,401	140,243	114,352	53,940	40,994	47,467	733,580	95,365
August	192,143	140,905	138,770	113,151	53,373	40,564	46,968	725,873	94,364
September	184,480	135,285	133,235	108,638	51,244	38,946	45,095	696,923	90,600
October	190,355	139,594	137,479	112,098	52,876	40,186	46,531	719,119	93,486

November	183,650	134,677	132,636	108,149	51,014	38,771	44,892	693,788	90,192
December	189,517	138,979	136,873	111,604	52,643	40,009	46,326	715,952	93,074
Total (year)	**2,265,580**	**1,661,425**	**1,636,252**	**1,334,175**	**629,328**	**478,289**	**553,808**	**8,558,856**	**1,112,651**
Total (year) dry**	**294,525**	**215,985**	**212,713**	**173,443**	**81,813**	**62,178**	**71,995**	**1,112,651**	

Dairy cows in the state of New Mexico produce 8.5 million tons of wet manure a year; equivalent to 1.1 million of dry manure. Thus, there is an opportunity and need to recycle 3,050 tons of dry manure each day. Manure excretion is concentrated in the top milk producing counties of: Chaves (806 tons/day), Curry (590 tons/day), Roosevelt (582 tons/day), and Doña Ana (475 tons/day).

Conclusions

Predictions of the seasonal variation of manure excretion creates a better opportunity for calculating manure use and recycling needs, and aids in addressing issues relative to bioenergy production, planning of storage, management, and assessment of environmental impacts. This approach to predicting manure excretion by dairy herds uses herd stochastic simulation modeling connected with the most recently published prediction parameters, and is a substantial contribution to current stage of manure prediction in New Mexico. Although some assumptions were needed and experimental data was lacking, the predictions by the developed model are considered valid and are consistent with local and national predictions. The model could likely be improved by collecting and including local experimental data to parameterize regional prediction equations of manure excretion.

The NM-Manure model is a “working-in-progress” application, which will be improved and updated with parameters on herd dynamics and manure excretion as soon as those become available. The stochastic herd dynamic simulation model, developed as structural part of the NM-Manure model, is considered a baseline model, in which other modules will be developed and connected with ample possibilities to study dairy farm systems in New Mexico.

Until fully validated, caution is advised when using results of the model outside the ranges found within the DHIA New Mexico records for milk productivity, pregnancy rates, and culling rates. These were used in the parameterization of NM-manure model.

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