UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

FACULTAD DE CIENCIAS QUÍMICAS, INGENIERÍA Y MEDICINA

PROGRAMAS MULTIDISCIPLINARIOS DE POSGRADO EN CIENCIAS AMBIENTALES

TESIS QUE PARA OBTENER EL GRADO DE

DOCTORADO EN CIENCIAS AMBIENTALES

TÍTULO: EFICIENCIA DE USO DE LOS RECURSOS NATURALES E IMPACTO AMBIENTAL POR SISTEMAS MODERNOS Y TRADICIONALES DE PRODUCCIÓN DE LECHE BOVINA

PRESENTA:

JUAN ANTONIO RENDÓN HUERTA

DIRECTOR DE TESIS:

JUAN MANUEL PINOS RODRÍGUEZ

ASESORES:

LETICIA YÁÑEZ ESTRADA

JUAN CARLOS GARCÍA LÓPEZ

ENERO 2014

UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

FACULTAD DE CIENCIAS QUÍMICAS, INGENIERÍA Y MEDICINA

PROGRAMAS MULTIDISCIPLINARIOS DE POSGRADO EN CIENCIAS AMBIENTALES

TESIS QUE PARA OBTENER EL GRADO DE

DOCTORADO EN CIENCIAS AMBIENTALES

TÍTULO: EFICIENCIA DE USO DE LOS RECURSOS NATURALES E IMPACTO AMBIENTAL POR SISTEMAS MODERNOS Y TRADICIONALES DE PRODUCCIÓN DE LECHE BOVINA

PRESENTA:

JUAN ANTONIO RENDÓN HUERTA

COMITÉ TUTELAR:

DIRECTOR: JUAN MANUEL PINOS RODRÍGUEZ

ASESOR: LETICIA YÁÑEZ ESTRADA

ASESOR: JUAN CARLOS GARCÍA LÓPEZ

SINODALES:

PRESIDENTE: JUAN MANUEL PINOS RODRÍGUEZ

SECRETARIO: LETICIA YÁÑEZ ESTRADA

VOCAL: JUAN CARLOS GARCÍA LÓPEZ

VOCAL: GREGORIO ÁLVAREZ FUENTES AFUENTES

VOCAL: IGNACIO DOMINGUEZ VARA

CRÉDITOS INSTITUCIONALES

PROYECTO REALIZADO EN:

UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ y UNIVERSITY OF CALIFORNIA, DAVIS, USA

CON FINANCIAMIENTO DE:

UC MEXUS-CONACYT Collaborative Grants and Sesnon Endowed Chair Fund (UC Davis)

A TRAVÉS DEL PROYECTO DENOMINADO:

REDUCCIÓN DE LAS EMISIONES ENTÉRICAS DE METANO EN GRANJAS LECHERAS

REDUCING ENTERIC METHANE EMISSIONS IN LARGE DAIRIES

AGRADEZCO A CONACYT EL OTORGAMIENTO DE LA BECA-TESIS

Becario No. 208836

EL DOCTORADO EN CIENCIAS AMBIENTALES RECIBE APOYO ATRAVÉS

DEL PROGRAMA NACIONAL DE POSGRADOS DE CALIDAD (PNPC)

A LA SECRETARÍA DE INVESTIGACIÓN Y POSGRADO DE LA UASLP POR EL APOYO DE MOVILIDAD EN ESTANCIA NACIONAL 2011

DEDICATORIA

A mi esposa Maribel Aguirre Salinas,

aprecio mucho el tiempo que me esperaste

y el apoyo que me has dado a lo largo de estos años.

A mis padres (Eduardo y Ma. Guadalupe)

y hermanos (Cristina y Luciano)

AGRADECIMIENTOS

Al Dr. Juan Manuel Pinos Rodríguez por aceptarme como estudiante doctoral, por su apoyo incondicional en la realización de esta tesis, por su interés en formarme profesionalmente como investigador, así como por enseñarme a redactar artículos científicos y por su preciada amistad.

A la Dra. Leticia Yáñez Estrada por su colaboración en la mejora de este proyecto.

Al Dr. Juan Carlos García López, por la asesoría otorgada y el apoyo que siempre me brindó.

Al Dr. Juan Rogelio Aguirre Rivera, por las facilidades que me dió para trabajar en el Instituto de Investigación de Zonas Desérticas, por sus atinados consejos y por darme la confianza de trabajar en equipo.

Al Dr. Juan Antonio Reyes Agüero por su apoyo y creer en mí.

A la Dra. Bertha Irene Juárez Flores por su amistad sincera y por considerarme en otros trabajos.

A los Doctores Gregorio Álvarez y Héctor Durán por su amistad y por la asesoría que me brindaron en los trabajos que realizamos conjuntamente.

Al Señor Enrique y Doña Nancy por los buenos momentos de convivencia.

Al personal que labora en el Instituto de Investigación de Zonas Desérticas: Paty, Roxana, Yureida, Marilu, Sr. Alberto, etc.

A mis compañeros de cubículo con los que compartí momentos muy agradables: Priscilla, Flor de María, Samuel, Octavio, Amaranta y Miguel Angel.

ACKNOWLEDGEMENTS

I want to thank to the Department of Animal Science of the University of California, Davis for having me in 2012.

To Dr. Ermias Kebreab for his support, patient, and for accept me and to be part of his team work in his lab.

To Dr. Jim Fadel and Dr. Anders Strathe for the Modelling course and for teach me the R program.

Thanks to friends in Sustainable Agriculture Modelling (SAM) lab: Laura Mie Jensen, Gustavo Cruz, Ranga Appuhami, Kristan Reed, Giussepe Todde, Luis Moraes.

To my cousins Luisa Lambert, Sara Rendón and Norma Treviño thanks for the huge support and hospitality during my stay in USA, I will never forget you.

ÍNDICE

Introducción general

A partir de la segunda mitad del siglo XX, el crecimiento demográfico comenzó a incrementarse a un ritmo más acelerado sobre todo en los países en vías de desarrollo. En el año 2010 se contabilizaron a nivel mundial un poco más de siete mil millones de personas y se calculó que para el 2050 esta cifra rebase los nueve mil millones de habitantes, lo que ha provocado que la producción de alimentos tanto agrícola como pecuario se intensifique a través de un mayor número de animales confinados en un área más restringida. Lo anterior dió pauta al escrutinio público de alimentos inocuos y bienestar animal, en especial por los grupos ambientalistas y protectores de los animales quienes culpan a los sistemas intensivos del cambio climático y del maltrato animal, bajo la justificante de que los sistemas tradicionales o menos intensivos son los más inocuos y sostenibles, lo cual no es necesariamente cierto. Los sistemas de producción de leche bovina, tanto los intensivos como los semi-intensivos y extensivos generan gases de efecto invernadero (CH_4, CO_2 y N_2O) y desechos orgánicos (heces y orina). Todos ellos hacen uso de recursos naturales (agua, suelo) y de energía externa para la producción de forrajes, transporte, iluminación y funcionamiento de maquinaría, entre otros. Por ello, es conveniente evaluar la sustentabilidad de los sistemas de producción de leche bovina con diferente grado de intensificación, usando como referencia la emisión de gases de efecto invernadero por unidad de producto alimentario generado, bajo la hipótesis de que los sistemas semi-intensivos contaminan igual que los sistemas intensivos modernos. Por lo anterior, el objetivo del presente estudio fue evaluar la eficiencia con que los sistemas de producción de leche bovina (intensivo y semi-intensivo) hacen uso de los recursos naturales e impactan al ambiente. Lo anterior desglosado en este documento por medio de cuatro estrategias, 1)

Revisión bibliográfica de modelos matemáticos utilizados para la estimación de gases de efecto invernadero en establos lecheros; 2) Comparación de emisiones de metano (entérico-estiércol), óxido nitroso y bióxido de carbono estimados con un modelo empírico, uno mecánico dinámico y los del IPCC nivel II, ilustrado en un inventario de emisiones de gases de efecto invernadero por las prácticas de manejo de ganado lechero en México entre 1970 y 2010; 3) Comparación de sistemas lecheros intensivos y semi-intensivos en la estimación de emisiones de CH_4 (entérico-estiércol), N_2O y CO_2, además, cotejando la eficiencia de producción de leche a través de un balance de nutrientes N, P y K excretados en estiércol y por el uso de recursos naturales (agua y suelo) y, 4) Simulación de rentabilidad e impacto ambiental del posible uso de energía alterna (digestores anaerobios y paneles solares) como estrategia de mitigación de gases de efecto invernadero.

Capítulo I. Modelos matemáticos para estimar y mitigar la emisión de gases de efecto invernadero en ganado lechero

Resumen general. El objetivo de este capítulo fue analizar y discutir los distintos modelos matemáticos que han sido generados para predecir emisiones de metano y nitrógeno excretado que puede ser convertido a óxido nitroso y establecer estrategias de mitigación de gases de efecto invernadero, producidos por el ganado lechero estabulado. Cabe mencionar que este trabajo fue enviado y aceptado para su publicación como capítulo en un libro que se titulará **“Zoonosis, Cambio Climático y Sociedad”** y será editado por la Universidad Autónoma del Estado de México.

MODELOS MATEMÁTICOS PARA ESTIMAR Y MITIGAR LA EMISIÓN DE GASES DE EFECTO INVERNADERO EN GANADO LECHERO

Juan Antonio Rendón-Huerta, Juan Manuel Pinos-Rodríguez, Ranga Appuhamy, Ermias Kebreab

Introducción

Dentro del sector agropecuario, el ganado lechero juega un papel importante en el sector alimentario, ya que la leche es un alimento rico en nutrientes esenciales que promueven efectos benéficos en la salud (Haug et al. 2007). En el 2010 la producción mundial de leche fue de alrededor de los 600 millones de toneladas, provenientes de 258 millones de vacas (FAOSTAT 2012). Los sistemas de producción de leche emiten gases de efecto invernadero (GEI), principalmente bióxido de carbono (CO_2), metano (CH_4) y óxido nitroso (N_2O) (Steinfeld et al. 2006). Estos gases contribuyen al incremento del calentamiento global ya que poseen la capacidad de absorber calor de los rayos infrarrojos que provienen del sol y presentan un potencial de absorción equivalente a $CO_2 = 1$, $CH_4 = 25$ y $N_2O = 298$ veces más que un kilogramo de CO_2, respectivamente (International Panel of Climate Change [IPCC] 2006). A escala global, dentro del sector pecuario, el proceso de producción de leche emite el 2.7% de los GEI de origen antropogénico, es decir estos gases se generan a través del proceso de producción de los alimentos para los animales, uso de fertilizantes, energéticos y combustibles, por la fermentación entérica de los propios alimentos en el rumen, el manejo del estiércol y el procesamiento y distribución de los productos generados por el propio sistema (FAO 2010). De los GEI que son emitidos a la atmósfera, el 52% son en forma de CH_4 entérico y por el manejo de estiércol, y 30% son emitidos a la atmósfera en forma de N_2O principalmente por la rápida volatilización de amonio presente en estiércol y por el uso de fertilizantes nitrogenados (FAO 2010; Oenema et al. 2005). Kebreab et al. (2008) menciona que la cuantificación de estos gases en rumiantes, en ocasiones es compleja y requiere de equipos costosos. Por lo cual, varios modelos matemáticos han sido desarrollado para predecir las pérdidas de energía a través de emisiones de GEI, relacionadas con la eficiencia de alimentación de rumiantes en confinamiento. El objetivo del presente documento es analizar y discutir los distintos modelos matemáticos que han sido generados para predecir emisiones de CH_4 y N excretado que puede ser convertido a N_2O y establecer estrategias de mitigación de GEI, producidos por el ganado lechero estabulado.

Gases de Efecto Invernadero y Cambio Climático

En el 2007, el IPCC reportó que la temperatura global promedio se había incrementado cerca de 0.74° C con respecto a la temperatura de inicio de siglo XXI, como consecuencia al incremento en las emisiones de GEI de origen antropogénico. Por ello, a nivel internacional, se estableció el reducir las emisiones de GEI como una medida para aminorar el calentamiento global. El organismo que regula y promueve la disminución progresiva del calentamiento global, es el Panel Intergubernamental de Cambio Climático (IPCC por sus siglas en ingles), a través del Protocolo de Kyoto, establecido en 1997 y ratificado en 2005, el cual establece que los 192 países que firmaron el protocolo (no ratificado por E.E.U.U. y abandonado por Canadá en 2011), deben reducir las emisiones antropogénicas globales de GEI, en un 5% con respecto a las reportadas en 1990, esto en el periodo comprendido entre 2008 y 2012 (United Nations [UN] 1998; Time 2011).

Generación y emisiones de metano entérico por rumiantes

El metano entérico es producido en el rumen de bovinos, cuando carbohidratos solubles e insolubles presentes en la ración son degradados bioquímicamente a pentosas y hexosas, y posteriormente fermentados en condiciones de anaerobiosis por los microrganismos ruminales para la producción de ácidos grasos volátiles (acetato, butirato y propionato), hidrógeno (H_2) y CO_2 (Moss et al. 2000). Los excesos de H_2 y CO_2 son utilizados como sustrato principal por microrganismos metanogénicos, clasificados como *Archaea*. Estos microrganismos generan CH_4 como producto del metabolismo, pero el que se genere CH_4 no es del todo negativo, ya que este proceso ayuda a equilibrar el ambiente en el rumen, reduciendo así los cambios bruscos de pH (Moss et al. 2000). El volumen mayor de CH_4 (87%) se produce en el rumen y es expulsado al ambiente por medio de eructos; el resto (13%) es producido en el colon (Murray et al. 1976). Kebreab et al. (2009), señalan que las emisiones de CH_4 por rumiantes no solo representa un problema ambiental, sino también una pérdida de productividad, debido a una ineficiencia en el uso de la energía de la ración por los animales, la cual oscila entre el 2 y 12% del consumo de energía bruta, dependiendo la calidad nutricional de la ración de buena a pobre, respectivamente (Johnson y Johnson. 1995).

Emisiones de óxido nitroso por la excreción de nitrógeno en estiércol

Otro GEI de importancia generado por los sistemas lecheros, es el óxido nitroso (N_2O) (Wrage et al. 2001), el cual es liberado cuando microrganismos transforman nitrógeno (N) ya sea en el suelo o en estiércol, a través de dos vías 1) por nitrificación de NH_4 a NH_3, y 2) por la incompleta desnitrificación de NH_3 a N_2. En gran medida la contribución de N_2O a la atmósfera, es cuando raciones para vacas lecheras sobrepasan los requerimientos de proteína propuestos por el National Resource Council [NRC] (2001) que es del 16% de proteína cruda (PC). Dijkstra et al. (2010) indicaron que los sistemas intensivos de producción de leche tienden a incrementar los contenidos de PC en las raciones para evitar problemas de insuficiencia de proteína y asegurar una mayor producción de leche. Pero cuando las raciones contienen contenidos altos de PC, una cantidad mayor de PC va a ser excretada en heces y orina, principalmente en forma de urea y amonio en la orina (NH_3), que al entrar en contacto con heces fecales, esté se volatiliza más rápidamente, teniendo como resultado emisiones de olores y N_2O (Castillo et al. 2000; Hristov et al. 2011). La estimación del IPCC (2006) indica que la liberación de N_2O al ambiente por kilogramo de N excretado varía de 0, 0.001 y 0.005 en digestores anaerobios, lagunas y almacenados al aire libre (meses), respectivamente. Así, los excesos de N excretado al ambiente en forma de NH_3 no sólo representa la emisión del gas, sino también riesgos de contaminación de agua superficial y subterránea, aunado a un impacto económico negativo para los productores (Dijkstra et al. 2010).

Generalidades de los Modelos Matemáticos

Un modelo matemático, según Thornley y France (2007) es una ecuación o serie de ecuaciones que representan el comportamiento de un sistema, y donde existe una correspondencia entre las variables del modelo y los valores observados [1].

$$Y = \mathrm{b} + \mathrm{a}X \qquad [1]$$

Dónde: Y es la variable dependiente, b es el intercepto, a es un escalar, y X es la variable independiente. France y Kebreab (2008) sugieren que para tener un mejor entendimiento del rol de los modelos matemáticos en las ciencias biológicas, las cuales incluyen ciencia animal, es necesario considerar la naturaleza y las implicaciones en la organización jerárquica, esto con el fin de delimitar el área de estudio en la que se va a enfocar el alcance de predicción del modelo, dichos niveles consideran macromoléculas (i - 3), organelos (i - 2), células (i - 1), tejidos (i), órganos (i + 1), organismos (i + 2) y poblaciones (i + 3). Cada nivel puede ser visto como un sistema, compuesto de subsistemas correspondientes al nivel anterior. De esta forma, (1) cada nivel tiene sus propios conceptos y lenguaje; (2) cada nivel es una integración de piezas provenientes de niveles inferiores, donde la reacción de un sistema al nivel i puede relacionarse con las reacciones en los niveles anteriores, y donde la descripción al nivel i -1 puede proveer un mecanismo de comportamiento al nivel i; (3) el éxito de operación de un nivel dado, requiere la acción de niveles anteriores para funcionar apropiadamente, pero no necesariamente en sentido contrario. Por ejemplo, un microrganismo puede ser extraído del rumen y puede crecer de cierta manera en condiciones *in vitro*, alejado de la integridad del rumen y del animal, pero el rumen y por consecuente el animal, no pueden desarrollarse por sí solos, sin la ayuda de microrganismos. En estos términos, los modelos matemáticos son desarrollados y utilizados para comprender los procesos en cada nivel.

Los modelos matemáticos son clasificados como determinísticos o estocásticos, estáticos o dinámicos y empíricos o mecánicos (Thornley y France 2007). Los modelos **determinísticos** hacen predicciones definitivas sin ninguna asociación con la distribución probabilística. Los modelos **estocásticos** incluyen elementos aleatorios así que las predicciones cuentan con distribución, por lo que técnicamente son difíciles de construir y de evaluar. Los modelos **empíricos** son aquellos en los cuales los datos experimentales son usados directamente para establecer relaciones entre variables, y por lo general se basan en un solo nivel jerárquico (por ejemplo, en un individuo). El enfoque deriva de la filosofía del empirismo y generalmente sigue metodologías estadísticas como la regresión lineal para describir hechos basados en observaciones y experimentación. Los modelos **mecánicos** involucran procesos que buscan el entendimiento de las causas donde se divide en un número de componentes que integran del sistema entero y hace un análisis de las interacciones más fuertes entre dichos componentes (Figura 1). Para ello, es necesario construir el modelo con al menos dos niveles jerárquicos (por ejemplo, órganos e individuo). El termino entendimiento, involucra las relaciones entre cantidades y mecanismos (proceso), entre dos o más compartimentos o variables que forman parte del nivel más bajo y el fenómeno que están prediciendo con respecto al nivel superior. Los modelos **estáticos** presentan uno o más parámetros interaccionando con otros, pero no contemplan el tiempo como variable. En los modelos **dinámicos**, las predicciones incluyen el tiempo como variable *t*, y en general presentan una serie de ecuaciones diferenciales ordinarias con respecto al tiempo.

$$\frac{\mathrm{d}y}{\mathrm{d}t} = f\,(P, E)$$

Dónde: *f* representa una función de tres cantidades *P* corresponde a uno o más parámetros, y *E* es una constante que denota cualquier efecto ajeno al sistema.

Modelos Matemáticos Para Predecir Emisiones de CH_4 Entérico

Los modelos matemáticos desarrollados para la predicción de CH_4 entérico son diversos, pero los más comúnmente utilizados son los empíricos (Blaxter y Clapperton 1965; Moe y Tyrrel 1979; Kirchgeβner et al. 1995; Mills et al. 2003; Ellis et al. 2007; y Jentsch et al. 2007). Estos modelos generalmente están construidos usando atributos como el consumo de materia seca, la proporción de forraje, el tipo de carbohidratos, el nivel de energía metabolizable, la digestibilidad y el tipo de ingredientes de la ración, entre otros (Tabla 1).

Mills et al. (2003) indicaron que las ecuaciones no lineales logran predicciones más precisas que los modelos lineales, debido que estos últimos, tienden a sobre predecir con forme el consumo de materia seca se incrementa porque no toman en cuenta la relación biológica de la porción digerible e indigerible, a excepción de los modelos de Jentsch et al (2007) que si consideran las fracciones degradables de los nutrientes.

Los modelos de predicción de metano entérico que usa el **IPCC**, básicamente están catalogados como modelos estáticos, descritos en niveles y grados de complejidad. En el nivel 1, que es el más sencillo, se asume una determinada cantidad de leche producida por año y un factor de emisión por región expresado en kg de CH_4 por animal al año. En el nivel 2, que es el que el IPCC recomienda, el factor de emisión es calculado utilizando el consumo promedio de alimento en términos de energía bruta (MJ/d), del cual asume que una proporción de esta energía es convertida a metano (Ym; 6.5%).

Un ejemplo de un modelo empírico que simula los procesos técnicos, ambientales y económicos de una granja lechera es el **DairyWise**. Este modelo se centra en los requerimientos de alimento del hato con la ayuda de otro modelo llamado DairyHerd, el cual estima la cantidad de forraje necesaria que se requiere producir dentro de la granja, siendo los principales el zacate y el ensilado de maíz. Las salidas correspondientes de este modelo incluyen el uso de energía, las emisiones de CO_2, (consumo de combustibles y energía), el CH_4 (entérico y del manejo de estiércol) y N_2O (de la excreción de N en estiércol y del uso de fertilizantes inorgánicos), la excreción de nutrientes y los costos financieros (Schils et al. 2007).

Ejemplo de un modelo estático es el llamado **Dairy** (Havlikova y Kroeze 2010), el cual predice una serie de contaminantes emitidos por las granjas lecheras, en relación a las prácticas de manejo dentro del sistema de producción (análisis de ciclo de vida), entre los cuales se encuentran NH_3, óxido de nitrógeno (NO), N_2O, CH_4, partículas suspendidas ($PM_{2.5}$ y PM_{10}) y nitrato (NO_3) en estiércol almacenado en sistemas sólidos y lodo líquido. De esta forma, éste modelo incluye riesgos de eutrofización, toxicidad humana y calentamiento global.

Un modelo de tipo dinámico-mecánico es el **Molly** (2007), el cual fue desarrollado por Baldwin (1995) en la Universidad de California (Davis), y el cual representa la utilización de nutrientes ingeridos por el bovino, donde la producción de metano entérico se basa en un balance de hidrógeno. Este modelo considera que exceso el H_2 producido durante la fermentación de carbohidratos y proteína a acido grasos volátiles AGV (acetato y butirato) es fraccionado y utilizado para el desarrollo microbiano, biohidrogenación de ácidos grasos insaturados y producción de AGV glucogénicos (propionato y valerato), en donde se asume que el remanente de H_2 es usado solamente para la generación de CH_4. La estequiometria de AGV en este modelo está basada en las ecuaciones desarrolladas por Murphy et al. (1982).

Otro modelo mecánico es **Cowpoll**, el cual está basado en el modelo del rumen propuesto por Dijkstra et al. (1992), en el cual se hace uso de una serie de 17 ecuaciones diferenciales no lineales. La producción de metano en el rumen y en el intestino fue añadida por Mills et al. (2001) siguiendo los principios de Baldwin (1995) (Figura 2). Posteriormente Kebreab et al. (2006) incorporó al modelo Cowpoll, la utilización de nitrógeno y fósforo. A diferencia de Molly, Cowpoll separa las poblaciones de microrganismos (amilolíticos, celulolíticos y protozoa) en el rumen para la fermentación de sustrato y la generación de AGV.

Los modelos mecánicos presentan una precisión mayor en la predicción de CH_4 en comparación con modelos de regresión lineal, debido a que los mecánicos utilizan un número mayor de variables tales como, consumo de materia seca, solubilidad y tasa de degradabilidad de ingredientes, velocidad de paso de las fracciones de líquidos y sólidos en el rumen, volumen y pH ruminal, y disponibilidad de H_2 en el rumen para generar CH_4 (Benchaar et al. 1998; Sejian et al. 2012).

Modelos Para Predecir Emisiones de Nitrógeno en Heces y Orina

Los modelos de predicción de nitrógeno excretado en heces y orina, relacionados con las emisiones de N_2O, en su mayoría son del tipo de regresión lineal y algunos no lineales, y en lo general consideran como variables independientes la ingesta de N en la dieta, material orgánica, consumo de materia seca, proteína degradable y no degradable (Bannink et al. 1999; Castillo et al. 2001; Nennich et al. 2006; Huhtanen et al. 2008; Arriaga et al. 2009; Higgs et al. 2012;) (Tabla 2). Los modelos de predicción de N en heces y orina, resultan más precisos cuando se toman como variables independientes el consumo de materia seca y el consumo de N, que cuando solamente se considera el consumo de N en la ración (Nennich et al. 2006; Huhtanen et al. 2008). Los modelos de predicción de Fox et al. (2004), Arriaga et al. (2009) y de Higgs et al. (2012), son derivados del modelo Cornell Net Carbohydrate and Protein System (CNCPS), el cual un modelo mecánico-empírico que simula la digestión de carbohidratos y proteínas, así como la velocidad de paso en el sistema digestivo y la absorción de energía y proteína en términos de eficiencia (Fox et al. 2004). Recientemente Higgs et al. (2012) realizaron mejoras de predicción al modelo, sobre las estimaciones de N excretado en heces, considerando como variables independientes además del consumo de N, el consumo de materia orgánica. En lo que respecta a las predicciones de N en orina, esté es calculado a través de la diferencia de N ingerido menos

N excretado en heces y leche. Kebreab et al. (2002), desarrollaron un modelo mecánico-dinámico de la excreción de N en heces, orina y leche, los autores mencionan que el modelo presenta una ligera subestimación en la predicción de N en heces, pero que presenta una mayor sensibilidad en la predicción de N en orina, conforme varía la degradabilidad de las proteínas. **Moorepark Dairy Systems Model** es un modelo estocástico, también llamado de granja completa que simula la digestión, absorción y excreciones de N depositado en heces y orina (Shalloo et al. 2004), tomando como base el ingreso de N al sistema en alimento y de fertilizantes. **DairyWise** (Schils et al. 2007), como se mencionó anteriormente, es un modelo empírico que hace un modelaje de entradas y salidas a nivel de granja, dentro de sus predicciones también están las estimaciones de excreciones de N en heces y orina, considera como variables independientes el consumo de N en la dieta, un coeficiente de proteína digerible y la cantidad de N absorbido, pero no menciona la precisión y exactitud de las predicciones.

Estrategias de Mitigación de GEI en Establos Lecheros en Confinamiento

La mejor estrategia para reducir el gasto de energía en mantenimiento, las pérdidas de energía en forma de CH_4 y de nutrientes como N y P es incrementando el nivel de producción reduciendo las excreciones de nutrientes en heces y orina, y ello sólo se logra con raciones de calidad (Taminga 1992; Yan et al. 2006). Al respecto, Beauchemin y McGinn (2006) siguieren que reduciendo las porciones de fibra e incrementando las cantidades de almidón y lípidos en la dieta, resulta en una estrategia para reducir las emisiones de CH_4 entérico. En efecto, en establos donde el ensilado de zacate o de leguminosas fue sustituido por ensilado de maíz, las producciones de leche fueron similares, pero las emisiones de GEI y de N se redujeron considerablemente (Groff y Wu

2005; Van Middelaar et al. 2012). De igual manera se ha observado que al aumentar la proporción de concentrados en la ración (de 47 a 68%), las vacas producen más leche y las emisiones de CH4 entérico se reducen hasta en un 20% (Aguerre et al. 2010). Ahora bien, el aumento de los concentrados en la ración implica necesariamente un balance del contenido de PC, es decir, se ha observado que las raciones para vacas altas productoras requieren no más del 16% de PC, con lo cual se cubre el requerimiento diario de N y se reduce la excreción de N, sin comprometer la producción de leche en términos de composición y rendimiento (Kebreab et al. 2002; Olmos-Colmenero y Broderick 2006; Arriaga et al. 2009).

Conclusión

Los distintos modelos matemáticos son una herramienta para predecir las emisiones de GEI (CH_4 entérico y N_2O por la excreción de N en heces y orina), sobre todo cuando no se cuenta con recursos necesarios para la cuantificación *in vivo*. El grado de precisión y exactitud de la predicción dependerá de la información disponible y del modelo que se utilice, es decir, mayor información como consumo de materia seca, composición de la dieta, rendimiento, se puede hacer uso de modelos de mayor precisión, como es el caso de los modelos mecánicos-dinámicos. Sin duda, una buena predicción es una herramienta útil para que los nutriólogos evalúen la calidad de los nutrientes en las raciones y desarrollen estrategias de mitigación de GEI a través de mejorar la eficiencia de producción.

Literatura citada

Aguerre, M.J., M.A. Wattiaux, J.M. Powell, G.A. Broderick y C. Arndt. 2011. Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. *Journal of Dairy Science* 94:3081-3093.

Arriaga, H., M. Pinto, S. Calsamiglia y P. Merino. 2009. Nutritional and management strategies on nitrogen and phosphorus use efficiency of lactating dairy cattle on commercial farms: An environmental perspective. *Journal of Dairy Science* 92:204-215.

Bannink, A., H. Valk y A.M. Van Vuuren. 1999. Intake and excretion of sodium, potassium, and nitrogen and the effects on urine production by lactating dairy cows. *Journal of Dairy Science* 82:1008-1018.

Baldwin, R. L. 1995. Modeling ruminant digestion and metabolism. Chapman & Hall, London, UK.

Beauchemin K.A. y S. M. McGinn. 2006. Methane emissions from beef cattle: Effects of fumaric acid, essential oil, and canola oil. *Journal of Animal Science* 84:1489-1496.

Benchaar, C., J. Rivest, C. Pomar y J. Chiquette. 1998. Prediction of methane production from dairy cows using existing mechanistic models and regression equations. *Journal of Animal Science* 76:617-627.

Blaxter, K.L. y J.L. Clapperton. 1965. Prediction of the amount of methane produced by ruminants. *British Journal of Nutrition* 19:511-522.

Castillo, A.R., E. Kebreab, D.E. Beever y J. France. 2000. A review of efficiency of nitrogen utilisation in dairy cows and its relationship with the environmental pollution. *Journal of Animal and Feed Sciences* 9:1-32.

Castillo, A.R., E. Kebreab, D.E. Beever, J.H. Barbi, J.D. Sutton, H.C. Kirby y J. France. 2001. The effect of protein supplementation on nitrogen utilization in lactating dairy cows fed grass silage diets. *Journal of Animal Science* 79:247-253.

Dijkstra, J., H.D. Neal, D.E. Beever y J. France. 1992. Simulation of nutrient digestion, absorption and outflow in the rumen: Model description. *Journal of Nutrition* 122:2239-2256.

Dijkstra, J., J. France, J.L. Ellis, E. Kebreab, S. López, J.W. Reijs y A. Bannink. 2010. Effects of nutritional strategies on simulated nitrogen excretion and methane emissions in dairy cattle. En *Modelling Nutrient Digestion and Utilization in Farm Animals*, editado por D. Sauvant, J. Van Milgen, P. Faverdin y N. Friggens. pp. 394-402. Netherlands.

Ellis, J.L., E. Kebreab, N.E. Odongo, B.W. McBride, E.K. Okine y J. France. 2007. Prediction of methane production from dairy and beef cattle. *Journal of Dairy Science* 90:3456-3467.

FAO. 2010. Greenhouse gas emissions from the dairy sector a life cycle assessment. Food and Agriculture Organization of the United Nations. Rome, Italy.

FAOSTAT. 2012. Food and Agriculture Organization statistical database (Agosto). http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor (2 Noviembre 2012).

Fox, D.G., L.O. Tedeschi, T.P. Tylutki, J.B. Russell, M.E. Van Amburgh, L.E. Chase, A.N. Pell y T.R. Overton. 2004. The Cornell Net Carbohydrate and Protein System model for evaluating herd nutrition and nutrient excretion. *Animal Feed Science and Technology* 112:29-78.

France, J. y E. Kebreab. 2008. Introduction. En *Mathematical Modeling in Animal Nutrition*, editado por J. France y E. Kebreab, pp. 1-11. CAB International, Wallingford, UK.

Groff, E.B. y Z. Wu. 2005. Milk production and nitrogen excretion of dairy cows fed different amounts of protein and varying proportions of alfalfa and corn silage. *Journal of Dairy Science* 88:3619-3632.

Haug, A., A.T. Høstmark y O.M. Harstad. 2007. Bovine milk in human nutrition – A review. *Lipids in Health and Disease* 6:25.

Havlikova, M. y C. Kroeze. 2010. Reducing environmental impact of dairy cattle: a Czech case study. *Integrated Environmental Assessment and Management* 6: 367–377.

Higgs, R.J., L.E. Chase y M.E. Van Amburgh. 2012. Development and evaluation of equations in the Cornell Net Carbohydrate and Protein System to predict nitrogen excretion in lactating dairy cows. *Journal of Dairy Science* 95:2004–2014.

Hristov, A.N., M. Hanigan, A. Cole, R. Todd, T.A. McAllister, P. M. Ndegwa y A. Rotz. 2011. Review: Ammonia emissions from dairy farms and beef feedlots. *Canadian Journal of Animal Science* 91:1-35.

Huhtanen, P., J.I. Nousiainen, M. Rinne, K. Kytölä y H. Khalili. 2008. Utilization and partition of dietary nitrogen in dairy cows fed grass silage-based diets. *Journal of Dairy Science* 91:3589–3599.

IPCC. 2006. *Emissions from livestock and manure management*. *Agriculture, Forestry and Other Land Use*. Intergovernmental Panel on Climate Change.

IPCC. 2007. Climate change 2007: *Synthesis report.* http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf (27 Noviembre 2012).

Jentsch, W., M. Schweigel, F. Weissbach, H. Scholze, W. Pitroff y M. Dermo. 2007. Methane production in cattle calculated by the nutrient composition of the diet. *Archives of Animal Nutrition* 61:10-19.

Johnson, K.A. y D.E. Johnson. 1995. Methane emissions from cattle. *Journal of Animal Science* 73:2483-2492.

Kebreab, E., J. France, J.A.N. Mills, R. Allison y J. Dijkstra. 2002. A dynamic model of N metabolism in the lactating dairy cow and an assessment of impact of N excretion on the environment. *Journal of Animal Science* 80:248-259.

Kebreab, E., J. France, B.W. McBride, N. Odongo, A. Bannink, J.A.N. Mills y J. Dijkstra. 2006. Evaluation of models to predict methane emissions from enteric fermentation in North American dairy cattle. En *Nutrient Digestion and Utilization in Farm Animals Modelling Approaches.* editado por E. Kebreab, J. Dijkstra, A. Bannink, W.J.J. Gerrits y J. France. pp. 299-313. CAB International, Wallingford, UK.

Kebreab, E., K.A. Johnson, S.L. Archibeque, D. Pape y T. Wirth. 2008. Model for estimating enteric methane emissions from United States dairy and feedlot cattle. *Journal of Animal Science* 86:2738-2748.

Kebreab, E., J. Dijkstra, A. Bannink y J. France. 2009. Recent advances in modeling nutrient utilization in ruminants. *Journal of Animal Science* 87(14 Suppl):E111-E122.

Kirchgeβner, M., W. Windisch y H.L. Müller. 1995. Nutritional factors for the quantification of methane production. En *Ruminant physiology: Digestion, metabolism, growth and reproduction, Proceedings of the 8th International*

Symposium on Ruminant Phosiology, editado por W. Engelhardt, S. Leonhard-Marek, G. Breves y D. Giesecke, pp. 333-348. Stuttgart: Ferdinand Enke Verlag.

Mills, J.A.N., J. Dijkstra, A. Bannink, S.B. Cammell, E. Kebreab y J. France. 2001. A mechanistic model of whole-tract digestion and methanogenesis in the lactating dairy cow: Model development, evaluation, and application. *Journal of Animal Science* 79:1584-1597.

Mills, J.A.N., E. Kebreab, C.M. Yates, L.A. Crompton, S.B. Cammell, M.S. Dhanoa, R.E. Agnew y J. France. 2003. Alternative approaches to predicting methane emissions from dairy cows. *Journal of Animal Science* 81:3141-3150.

Moe, P.W. y H.F. Tyrrell. 1979. Methane production in dairy cows. *Journal of Dairy Science* 62:1583-1586.

Moss, A.R., J.P. Jouany y J. Newbold. 2000. Methane production by ruminants: its contribution to global warming. *Annales de Zootechnie* 49:231-253.

Murphy, M.R., R.L. Baldwin y L.J. Koong. 1982. Estimation of stoichiometric parameters for rumen fermentation of roughage and concentrate diets. *Journal of Animal Science* 55:411-421.

Murray, R.M., A.M. Bryant y R.A. Leng. 1976. Rates of production of methane in the rumen and large intestines of sheep. *British Journal of Nutrition* 36:1-14.

Nennich, T.D., J.H. Harrison, L.M. VanWieringen, N.R. St-Pierre, R.L. Kincaid, M. A.Wattiaux, D.L. Davidson y E. Block. 2006. Prediction and evaluation of urine and urinary nitrogen and mineral excretion from dairy cattle. *Journal of Dairy Science* 89:353–364.

NRC. 2001. Nutrient Requirements of Dairy Cattle. National Resource Council. Washington, DC: National Academy Press.

Oenema O., N. Wrage, G.L. Velthof, J.W. Van Groeningen, J. Dolfing y P.J. Kuikman. 2005. Trends in global nitrous oxide emission from animal production systems. *Nutrient Cycling in Agroecosystems* 72:51-65.

Olmos-Colmenero, J.J. y G.A. Broderick. 2006. Effect of dietary crude protein concentration on milk production and nitrogen utilization in lactating dairy cows. *Journal of Dairy Science* 89:1704–1712.

Shalloo, L., P. Dillon, M. Rath y M. Wallace. 2004. Description and validation of the Moorepark Dairy System Model. *Journal of Dairy Science* 87:1945-1959.

Sejian, V., I. Shekhawat, V. Ujor, T. Ezeji, J. Lakritz y R. Lal. 2012. Global Climate Change: Enteric Methane Reduction Strategies in Livestock. En *Environmental Stress and Amelioration in Livestock Production,* editado por V. Sejian, S.M.K. Naqvi, T. Ezeji, J. Lakritz y R. Lal, pp. 469-499. Springer-Verlag, Berlin Heidelberg.

Schils, R.L.M., A.Verhagen, H.F.M. Aarts, P.J. Kuikman y L.B.J. Šebek. 2006. Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in the Netherlands. *Global Change Biology* 12:382-391.

Schils, R.L.M., M.H.A. de Haan, J.G.A. Hemmer, A. van den Pol-van Dasselaar, J.A. de Boer, A.G. Evers, G. Holshof, J.C. van Middelkoop y R.L.G. Zom. 2007. DairyWise, a whole-farm dairy model. *Journal of Dairy Science* 90:5334-5346.

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales y C. De Haan. 2006. *Livestock's long shadow: Environmental issues and options*. Rome, Italy: Food and Agriculture Organization.

Tamminga, S. 1992. Nutrition management of dairy cows as a contribution to pollution control. *Journal of Dairy Science* 75:345-357.

Time. 2011. “Kyoto for Canada is in the past. As such, we are invoking our legal right to formally withdraw.” (11 diciembre 2011). http://science.time.com/2011/12/12/canadian-environment-minister-peter-kent-announces-that-the-country-is-pulling-out-of-kyoto-protocol/ (10 diciembre 2012).

Thornley, J.H.M. y J. France. 2007. Role of Mathematical model. En *Mathematical Models in Agriculture, Quantitative Methods for the Plant, Animal and Ecological Science*, editado por J.H.M. Thornley y J. France, pp. 1-18. CAB International, Wallingford, UK.

UN. 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. United Nations.

Van Middelaar, C.E., P.B.M. Berentsen, J. Dijkstra y I.J.M. De Boer. 2012. Evaluation of a feeding strategy to reduce greenhouse gas emissions from milk production: The level of analysis matters. Production, Management and the Environment: Environmental Quality. *Journal of Animal Science* 90: Suppl. 3/*Journal of Dairy Science* 95(Suppl. 2): 707.

Wrage, N., G.L. Velthof, M.L. van Beusichem y O. Oenema. 2001. Role of nitrifier denitrification in the production of nitrous oxide. *Soil Biology & Biochemistry* 33:1723-1732.

Yan, T., S. Mayne y M.G. Porter. 2006. Effects of dietary and animal factors on methane production in dairy cows offered grass silage-based diets. *International Congress Series* 1293:123-126.

Tabla 1. Modelos matemáticos para la predicción de CH_4 entérico

Ecuación	Modelo	Referencia
CH_4 (MJ/d) = 5.447 + (0.469 × EDMI) + (MM × [9.930 − 0.21 × (EDMI)/100 × GEI])	Empírico	Blaxter y Clappterton 1965
CH_4 (MJ/d) = 0.341 + (0.511 × NSC) + (1.74 × HC) + (2.652 × C)	Empírico	Moe y Tyrrel 1979
Cowpoll	Mecánico	Dijkstra et al. 1992; Mills et al. 2001
CH_4 (g/d) = 63 + (79 × CF) + (10 × NFE) + (26 × CP) – (212 × EE)	Empírico	Kirchgeβner et al. 1995
CH_4 (MJ/d) = 5.93 + (0.92 × DMI)	Empírico	Mills et al. 2003
CH_4 (MJ/d) = 8.25 + (0.07 × MEI)	Empírico	Mills et al. 2003
CH_4 (MJ/d) = 1.06 + (10.27 × Dietary forage proportion) + (0.87 × DMI)	Empírico	Mills et al. 2003
CH_4 (MJ/d) = $56.27 - (56.27 + 0) \times e^{[-0.028 \times DMI]}$	Empírico £	Mills et al. 2003
CH_4 (MJ/d) = $45.89 - (45.89 + 0) \times e^{[-0.003 \times MEI]}$	Empírico£	Mills et al. 2003
CH_4 (g/d) = (20 × Conc. Intake) + (22 × Corn silage intake) + (27 × Grass intake)	Empírico	Schils et al. 2006
CH_4 (Gg/año) = EF × Núm	Estático	IPCC 2006, nivel 1

CH$_4$ (Gg/año) = [(GE × (Ym/100) × 365)/55.65] × Núm	Empírico	IPCC 2006, nivel 2
CH$_4$ (MJ/d) = 8.56 + (0.14 × forage)	Empírico	Ellis et al. 2007
CH$_4$ (MJ/d) = 3.23 + (0.81 × DMI)	Empírico	Ellis et al. 2007
CH$_4$ (MJ/d) = 4.08 + (0.0678 × MEI)	Empírico	Ellis et al. 2007
CH$_4$ (MJ/d) = 2.16 + (0.493 × DMI) – (1.36 × ADF) + (1.97 × NDF)	Empírico	Ellis et al. 2007
CH$_4$ (MJ/d) = 3.27 + (0.74 × DMI)	Empírico[€]	Ellis et al. 2007
CH$_4$ (kJ/d) = (1.62 × DCP) – (0.38 × DCF) + (3.78 × DCF) + (1.49 × D N-FE)	Empírico	Jentsch et al. 2007
NFE = OM – (CP + EE + CF)		
CH$_4$ (kJ/d) = (1.28 × DCP) – (0.31 × DCF) + (1.31 × DSt) + (1.16 × DSu) + (2.24 × D-NFR)	Empírico	Jentsch et al. 2007
NFR = OM – (CP + EE + St + Su + CA)		
DairyWise	Empírico	Schils et al. 2007
Molly	Mecánico	Baldwin et al. 1995
Dairy	Estático	Havlikova y Kroeze 2010

EDMI = Ingesta de energía digerible sobre el mantenimiento (% de GE), MM = Múltiplo de mantenimiento, GEI =consumo de energía bruta (MJ/d), NSC = Carbohidratos no estructurales (kg/d), HC = Hemicelulosa (kg/d), C = Celulosa (kg/d), CF = Fibra cruda (kg/d), NFE = Extracto libre de N (kg/d), CP = Proteína cruda (kg/d), EE = Extracto etéreo (grasa, kg/d), DMI = Consumo de materia seca (kg/d), MEI = Ingesta de energía metabolizable (MJ/d), Dietary forage proportion = Proporción de forraje en la dieta (decimales), Conc. Intake = Consumo de concentrado (kg/d), Corn silage intake = Consumo de ensilado de maíz (kg MS/d), Grass intake = Consumo de zacates (kg MS/d), FE = Factor de emisión, Núm = Número de individuos, GE = Energía bruta (MJ/d), Ym = factor de conversión de GE en metano, equivalente a 6.5% para ganado lechero, forage = forraje (%), DCP = Proteína cruda digerible (g/d), DCF = Grasa cruda digerible (g/d), DCF = Fibra cruda digerible (g/d), D-NFE= Extracto digerible libre de N (g/d), DSt = Almidón digerible (g/d), DSu = Azúcares digeribles (g/d), D-NFR = Residuo digerible libre de N (g/d), OM = Materia orgánica (g), St = Almidón (g), Su = Azúcares (g), CA = Ceniza cruda (g).

[£] Regresión no lineal.

[€] Ecuación desarrollada para ganado lechero y de engorda.

Tabla 2. Modelos que predicen excreciones de nitrógeno en heces y orina

Ecuación	Modelo	Autor
$UN = 75.18 + (0.719 \times (D_N - M_N))$	Empírico	Bannink et al. 1999
$D_N = -42.5 + (0.738 \times NI)$		
$M_N = 46.62 + (3.681 \times Milk)$		
$FN = 46.6 + (0.2 \times NI)$	Empírico	Castillo et al. 2001
$UN = 21.0^{0.0046\ (NI)}$	Empírico$^{£}$	Castillo et al. 2001
FN; Calculado con ecuaciones diferenciales	Mecánico	Kebreab et al. 2002 (Figura 3)
UN; Calculado con ecuaciones diferenciales		
$FN = [(FEPB3 + FEPC + FEBCP + IDM) \times 0.09]/6.25$	Empírico	Fox et al. 2004
$UN = \{(NI) - [SPA + (Milk \times MilkCP \times 10/0.93) + MPPreg + MPg + Fecal\ CP]\}/6.25$	Empírico	Fox et al. 2004
Moorepark Dairy Systems Model	Estocástico	Shalloo et al. 2004
$UN = (RDP \times 0.0628) + 55.6$	Empírico	Nennich et al. 2006
$UN = (BW \times 0.254) - (Milk \times 1.03) + (NI \times 0.2101) + (MUN \times 5.07) + (MTP \times$	Empírico	Nennich et al. 2006

$21.8) – (MF \times 6.5) - 138.8$		
DairyWise	Empírico	Schils et al. 2007
$UN = -126 + (NI \times 0.676)$	Empírico	Huhtanen et al. 2008
$FN = -21 + (DMI \times 6.73) + (NI \times 0.101)$	Empírico	Huhtanen et al. 2008
$FN = 0.329 \times (NI + 29.8)$	Empírico	Arriaga et al. 2009
$UN = 0.164 \times NI^{1.13}$	Empírico[€]	Arriaga et al. 2009
$FN = [\{[NI \times (1 – 0.842)] + 4.3\} \times OMI] \times 1.20$	Empírico	Higgs et al. 2012

UN = Nitrógeno excretado en orina (g/d), ($D_N – M_N$) = diferencia entre N aparentemente digerido y N excretado en leche (g/d), Milk = Leche (kg/d), NI = Nitrógeno consumido (g/d), FN = Nitrógeno excretado en heces, DMI = Consumo de materia seca (kg/d), FEPB3 = Cantidad de proteína de la fracción B3 en heces (g/d), FEPC = Cantidad de proteína de la fracción C en heces (g/d), FEBCP = Cantidad de proteína microbiana en heces (g/d), IDM = Materia seca indigerible (g/d), SPA = Requerimiento de proteína neta para perdidas por pelaje (g/d), MPPreg = Requerimiento de proteína metabolizable para la preñez (g/d), MPg = Requerimiento de proteína metabolizable para crecimiento (g/d), MilkCP = Proteína cruda en leche (g/d), Fecal CP = Proteína cruda en heces (g/d), RDP = Proteína degradable en el rumen(g/d), BW = Peso vivo (kg/animal), MUN = Nitrógeno ureico en leche (mg/dL), MTP = Porcentaje de Proteína en leche (%), MF = Porcentaje de grasa en leche (%), OMI = Consumo de materia orgánica (kg/d).

[£] Regresión no lineal.

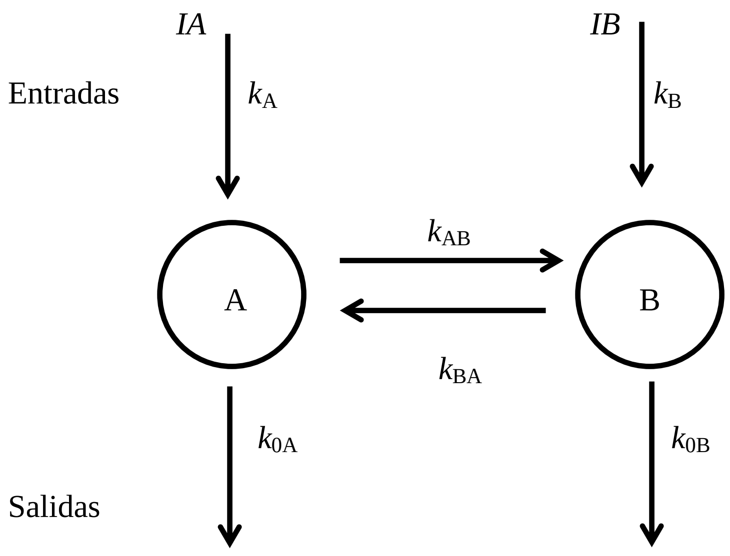

Figura 1. Representación gráfica de un modelo mecánico usando dos compartimentos, A y B, las flechas simbolizan flujos (Dos ecuaciones diferenciales).

Ecuaciones diferenciales del sistema

$$\mathrm{d}QA/\mathrm{d}t = -k_{AB}A + k_{BA}B - k_{0A}A + IA$$

$$\mathrm{d}QB/\mathrm{d}t = k_{AB}A - k_{BA}B - k_{0B}B + IB$$

QA = masa del compartimento A

QB = masa del compartimento B

kij = constante de velocidad de flujo del compartimento i al j (1/tiempo)

ki_0 = constante de velocidad de excreción del compartimento i, hacia la salida del sistema (1/tiempo)

Ii = constante de inyección de una sustancia en el compartimento i (masa/tiempo)

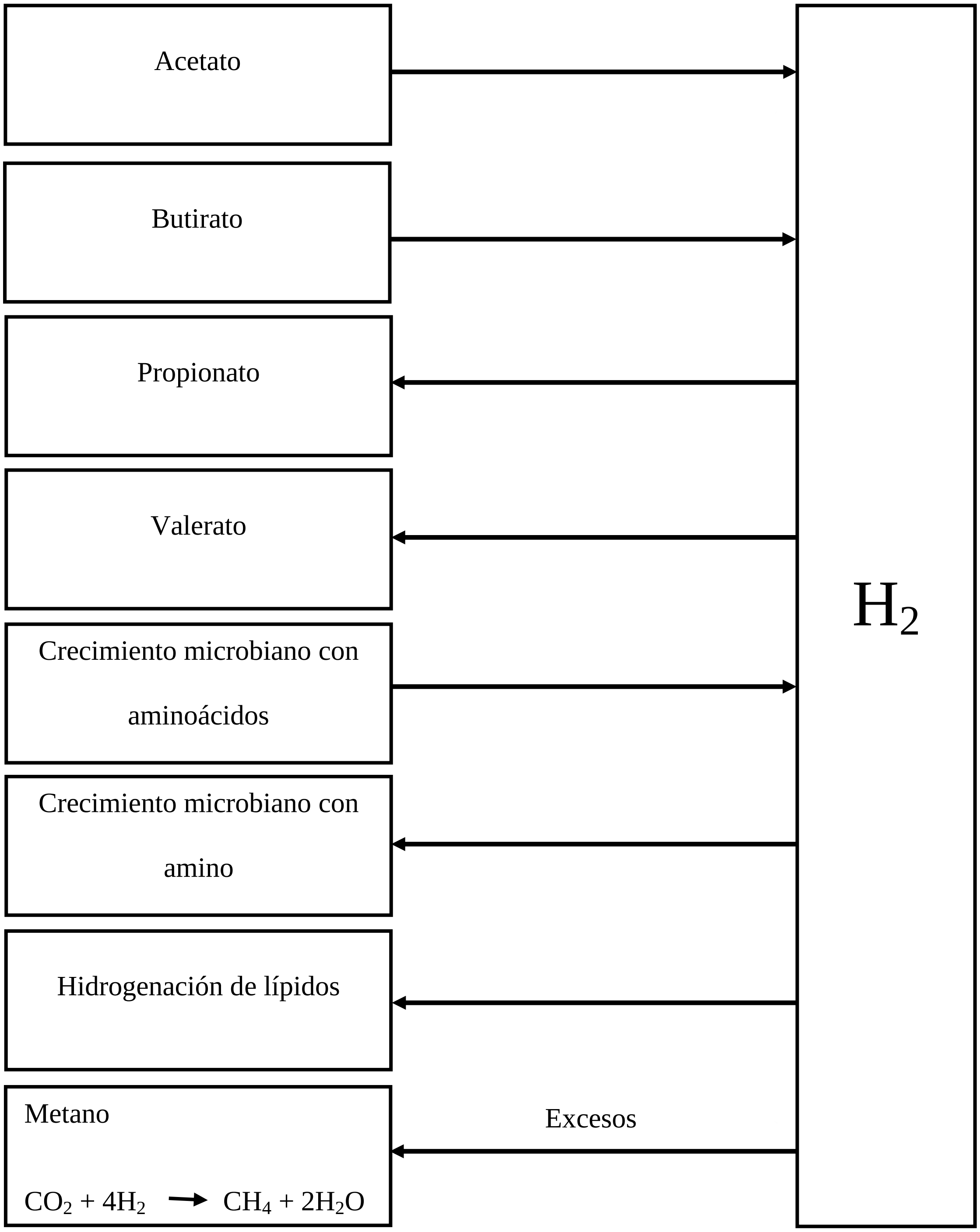

Figura 2. Representación esquemática de una fracción del modelo dinámico Cowpoll, que simula las fuentes y depósitos de hidrógeno en la generación de CH_4 entérico (Kebreab et al. 2006:Figura 27.1 [traducido por Rendón]).

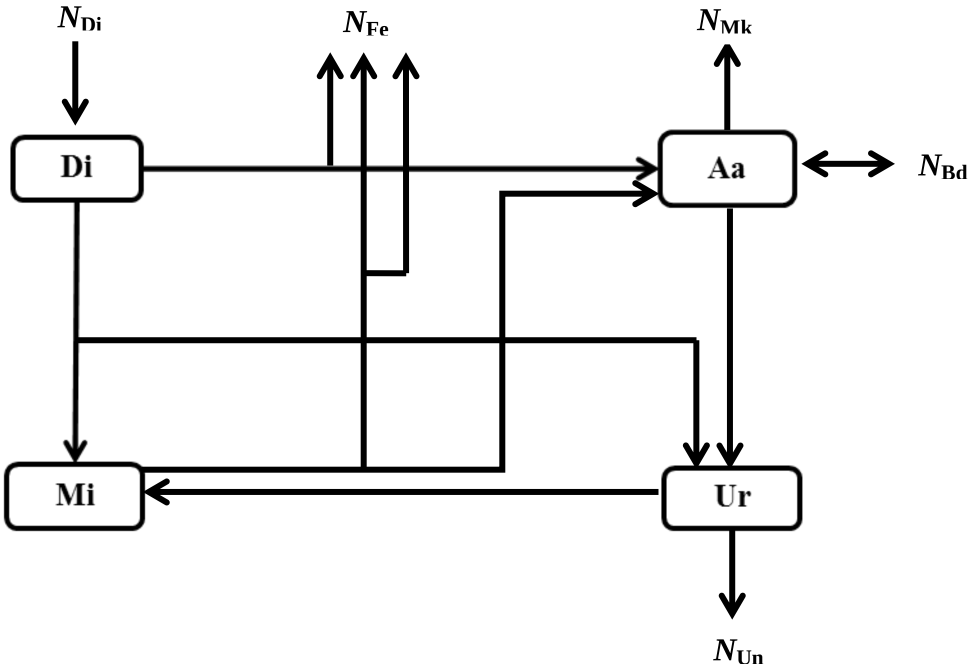

Figura 3. Representación gráfica del modelo mecánico de Kebreab et al. (2002: Figura 1[traducido por Rendón]), para predecir nitrógeno excretado, los cuadros simbolizan compartimentos de proteína en (Di = Dieta, Aa = Aminoácidos, Mi = Microbiana y Ur = Urea y amonio), y sus respectivas salidas en forma de (Fe = Heces, Mk = Leche, Bd = Músculo, Ue = Orina), las flechas indican los flujos de nitrógeno.

Capítulo II. Trends in greenhouse gas emissions from dairy cattle in Mexico between 1970 and 2010

Resumen general. El objetivo de este estudio fue estimar y evaluar las tendencias de emisiones de gases de efecto invernadero (GEI) como metano (CH_4) y óxido nitroso (N_2O) por vacas productoras de leche en México del año 1970 al 2010. Para ello se utilizaron diferentes modelos matemáticos que usan la composición de la dieta para estimar las emisiones de metano entérico. Las emisiones de CH_4 y N_2O generados en el estiércol fueron estimados con las guías del Panel Intergubernamental de Cambio Climático (IPCC). Los resultados indicaron que el manejo y las prácticas modernas de producción en vacas lecheras, incrementó la eficiencia de conversión de alimento en leche en un 32%, así como la producción de leche por vaca en 62%. Así, las emisiones de GEI por unidad de producto (1 kg de leche) para 2010 se redujeron en un 30, 25 y 30% para CH_4, N_2O y para el total emisiones comparado con 1970. Este manuscrito fue enviado al Animal Production Science (ISSN: 1836-0939) y publicado en línea, DOI: http://dx.doi.org/10.1071/AN12327.

CSIRO PUBLISHING

Animal Production Science
http://dx.doi.org/10.1071/AN12327

Trends in greenhouse gas emissions from dairy cattle in Mexico between 1970 and 2010

J. A. Rendón-Huerta[A,E], *J. M. Pinos-Rodríguez*[B], *J. C. García-López*[B], *L. G. Yáñez-Estrada*[C] *and E. Kebreab*[D]

[A]Programa Multidisciplinario de Posgrado en Ciencias Ambientales, Universidad Autónoma de San Luis Potosí (UASLP), Avenida Manual Nava 201, Zona Universitaria, 78290, San Luis Potosí, Mexico.
[B]Instituto de Investigación de Zonas Desérticas, UASLP, Altair No. 200. Fraccionamiento del Llano, 78377, San Luis Potosí, Mexico.
[C]Departamento de Toxicología Ambiental, Facultad de Medicina, UASLP, Avenida Manuel Nava 201, Zona Universitaria, 78290, San Luis Potosí, Mexico.
[D]Department of Animal Science, University of California, Davis CA, 95616, USA.
[E]Corresponding author. Email: jrendonhuerta@hotmail.com

Abstract. The objective of the present work was to estimate and assess trends in greenhouse gas (GHG) emissions, particularly methane (CH_4) and nitrous oxide (N_2O), from dairy cows in Mexico from the base year of 1970 to 2010. Empirical and mechanistic models were used to estimate enteric methane emissions based on chemical composition of diets. Methane from manure was calculated using Intergovernmental Panel for Climate Change (IPCC) and US Environmental Protection Agency recommended equations. N_2O emission was calculated according to IPCC recommendations. Compared with the 1970s, current management practices using modern dairy cows increased feed conversion efficiency 32% and milk yield 62%. GHG emission intensity (i.e. emissions per unit of product) was reduced 30%, 25% and 30% for CH_4, N_2O and total emissions, respectively. The study showed that although GHG emissions in absolute terms increased in the past 40 years, emission intensity decreased due to higher level of production. This trend is likely to continue in the future, assuming milk production follows the same increasing trend as in other countries in North America.

Additional keywords: environmental impact, methane, milk production, nitrous oxide.

Received 19 September 2012, accepted 4 April 2013, published online 21 May 2013

Introduction

In Mexico, livestock activities use 110 million hectares, 28% of which are located in hot and humid areas, 23% in central part of the country and 49% in desert and semi-desert areas that are mainly devoted to poultry farming, swine breeding and production of bovine milk and meat (SEMARNAT–INE 2002). Bovine milk is one of the most in demand products in Mexico because it is considered to be a good source of energy and protein (Espinoza *et al.* 2005). The majority of milk is produced in the states of Coahuila, Durango, Jalisco, Estado de Mexico, Veracruz, Chihuahua, Querétaro, Guanajuato, Hidalgo and Aguascalientes (SIAP–SAGARPA 2008). Dairy production systems in the 1970s were based on grazed pasture and were characterised by low levels of low milk production (9.2 kg/day) (FAO 2012); in contrast, current intensive systems make better use of natural resources and minimise the intensity of greenhouse gas (GHG) emissions (i.e. emission per product) (Capper *et al.* 2008). Capper *et al.* (2009) reported that intensive systems are more efficient in utilising energy, which reduces environmental impact of dairy farming. Thus, recent research in animal science has been focussed on improving feed efficiency and other mitigation strategies to reduce emission intensity.

Direct measurement of GHGs such as methane (CH_4) and nitrous oxide (N_2O) is complex and requires expensive equipment. However, several simple empirical and more complex mechanistic models have been developed to estimate GHG emissions by dairy cattle. Mechanistic models allow prediction of CH_4 and N_2O emissions on the basis of type and amount of nutrient intake (Kebreab *et al.* 2006). In Mexico, there is a lack of studies in this field and the most recent GHG census was made using data from 1990–2002 (SEMARNAT–INE 2002). In the census, IPCC Tier I guidelines were used to calculate enteric CH_4 emissions. A fixed emission factor of 72 kg CH_4/year (applicable to all Latin American countries) was used, assuming annual milk production of 800 kg. The objective of the present work was to estimate and assess trends in CH_4 and N_2O emissions from the dairy cow population in Mexico from the base year of 1970 to 2010, by using mathematical models.

Materials and methods

Data sources

Analysis of the environmental impact of dairy systems in Mexico was conducted on the basis of the methodology described by Capper *et al.* (2008, 2009) (Table 1), which requires estimates of herd size, milk production and milk yield (Fig. 1; FAO 2012). For this study, experiments that report dietary characteristics (Table 2) needed to run the models described below were chosen. Therefore, data from Cabello *et al.* (1971), Mendoza-Martínez *et al.* (1986), Plascencia-Jorquera *et al.* (1999), Ayala *et al.* (2001) and Weiss and Pinos-Rodríguez (2009) were obtained. Cow's nutritional requirements were calculated using the National Research Council recommendations (NRC 2001). Dairy cows were assumed to be managed under a confinement system. In the study, human population in Mexico and *per capita* consumption were also considered as variables affecting milk production and, consequentially, GHG emissions (CONAPO 2005; INEGI 2011).

Table 1. Characteristics of the dairy production systems in Mexico

Variable	1970	2010
Breed	90% Holstein^A	95% Holstein^E
Milk yield per cow (kg/year)	2800^B	4541^B
Lactation period (days)	305^A	305^D
Milk fat content (%)	3.50^A	3.31^D
Milk protein content (%)	4.00^A	3.04^D
Main forage source	Corn silage	Corn silage and alfalfa silage^D
Type of diet	Forage + concentrate^C	Total mixed rations^D

^{A}Saucedo (1984).
^{B}FAO (2012).
^{C}Cabello *et al.* (1971).
^{D}Pinos-Rodríguez *et al.* (2010).
^{E}SAGARPA (2010).

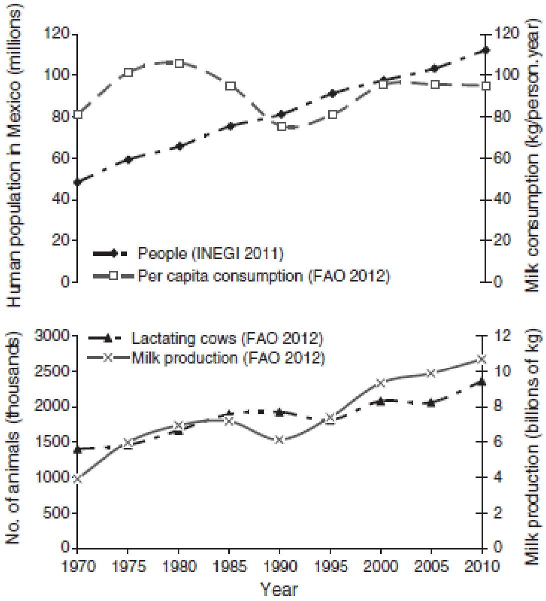

Fig. 1. Changes in the human population, *per capita* consumption, lactating cows and milk production in Mexico.

Mathematical models

To estimate enteric fermentation, three models were selected on the basis of input data requirement, their ease of application and widespread use to predict CH_4 emissions and also their potential relevance to Mexican dairy production system. Daily enteric CH_4 production was calculated using two empirical models (Moe and Tyrrell 1979; IPCC 2006) and a mechanistic model COWPOLL (based on Dijkstra *et al.* 1992).

Moe and Tyrrell equation

An empirical model of Moe and Tyrrell (1979) that takes into consideration the relationship between intake and diet composition was used to estimate CH_4 emissions. The model is described as follows:

$$\begin{aligned}\text{Methane (MJ/day)} &= 3.38 + 0.51\ \text{NFC (kg/day)} \\ &\quad + 2.14\ \text{HC (kg/day)} + 2.65\ \text{C (kg/day)},\end{aligned} \tag{1}$$

where NFC is non-fibre carbohydrate, HC is hemicellulose and C is cellulose.

Intergovernmental Panel for Climate Change (IPCC) Tier II

The IPCC, in its revised reference manual (IPCC 2006), outlined two methodologies to estimate CH_4 emissions from livestock enteric fermentation, namely Tier I and Tier II. A third methodology, Tier III, is also recommended for countries with detailed information on animal and diet characteristics using mechanistic models. Tier I is a simplified approach that assigns default CH_4 emissions for distinct animal categories. Therefore, only readily available animal population data are needed to estimate emissions. When more detailed livestock data are available, Tier II method estimates enteric CH_4 emissions from ruminants on the basis of their gross energy intake (GEI, MJ/day) and the default CH_4 conversion rate (*Ym*, %GEI). Feed intake is estimated from bodyweight, average daily gain, milk production per day, average amount of work performed per day, percentage of cows that give birth in a year, and feed digestibility. Methane conversion rate is the extent to which feed energy is converted to CH_4. The default *Ym* value proposed by IPCC (2006) is 6.5% ± 1% for dairy cows.

$$EF = \frac{GE \cdot \left(\frac{ym}{100}\right) \cdot 365}{55.65}, \tag{2}$$

where EF is an emission factor (kg CH_4/animal.year), GE is the gross energy intake (MJ/day), *Ym* is the CH_4 conversion factor (%) and the factor 55.65 is the energy content of CH_4 (MJ/kg).

COWPOLL

The original rumen model developed by Dijkstra *et al.* (1992) was used as the base model. The model contains a series of dynamic, deterministic and non-linear differential equations. Designed to simulate the digestion, absorption and outflow of nutrients in the rumen, the model contains 17 state variables that

Table 2. Diet composition for mature cows

Energy content of methane calculated with the models (MJ/day) was divided between the factor 55.65 (MJ/kg CH_4)

Item	Cabello *et al.* (1971)	Mendoza-Martínez *et al.* (1986)	Plascencia-Jorquera *et al.* (1999)	Ayala *et al.* (2001)	Weiss and Pinos-Rodríguez (2009)
			Ingredient (% of DM)		
Corn silage	74.0	–	–	–	26.8
Alfalfa silage	–	58.3	45.0	15.0	13.2
Alfalfa hay	–	–	–	26.0	–
Concentrate 16% crude protein	–	–	–	25.0	–
Corn	4.8	–	44.6	–	–
Sesame paste	1.8	–	–	–	–
Wheat bran	6.5	–	–	–	–
Brewers grains dried	6.5	–	–	–	–
Rice bran	5.5	–	–	–	–
Sorghum grains	–	25.0	–	20.0	–
Safflower	–	8.4	–	–	–
Ground corn	–	–	–	–	20.8
Hominy	–	–	–	–	4.0
Soybean hulls	–	–	–	–	8.9
wheat middings	–	–	–	–	7.0
Soybean meal 44% crude protein	–	–	–	–	8.7
Treated soybean meal	–	–	–	–	3.4
Distillers grains	–	–	–	–	5
Meat meal	–	–	1.0	10.25	–
Blood meal	–	–	1.0	–	–
Feather meal	–	–	1.0	–	–
Molasses	–	4.2	5.75	–	–
Limestone	–	–	–	–	1.08
Magnesium oxide	–	–	–	–	0.03
Poultry litter	–	2.1	–	–	–
Urea	–	0.6	0.43	–	–
Phosphate rock	0.52	0.9	0.32	0.5	–
Salt	0.26	0.5	0.5	1.0	–
Mineral mix	0.1	–	–	1.5	0.49
Vitamin A	0.08	–	–	–	–
			Model predictions (MJ/day)		
Moe and Tyrrell (1979)	16.1	16.1	16.4	16.7	15.9
COWPOLL (based on Dijkstra *et al.* 1992)	13.8	12.5	15.5	15.3	15.8
IPCC (2006)	17.9	17.7	17.2	17.6	18.6

represent N, carbohydrate (NDF, starch, and sugar), lipid and volatile fatty acid pools. Three microbial groups, namely amylolytic and celluloytic bacteria, and protozoa, are represented in the model. Using the principle of Baldwin (1995), CH_4 production in the rumen and hindgut was added to the rumen model by Mills *et al.* (2001). The principle was based on excess hydrogen produced during fermentation being partitioned between its use for microbial growth, biohydrogenation of unsaturated fatty acids and the production of glucogenic volatile fatty acids (Mills *et al.* 2001). The model was run for several days with a time-step of 1 h, until a steady-state was achieved.

The total amount of enteric methane (ECH_{4j}, kg/year) produced by the Mexican dairy cattle herd in Year *j* can be calculated as follows:

$$ECH_{4j} = C_j \times EEF_j, \tag{3}$$

where C_j is the total number of dairy cows in Year *j*, and EEF_j is the corresponding annual CH_4 enteric emission factor for Year *j*.

Enteric CH_4 emissions were considered to be zero for calves (birth to pasture), as described by Le Du *et al.* (1976) who observed that at 90 days of age, calves on milk consumed less than 1 kg/day of herbage.

Manure CH_4 emissions were estimated using the IPCC Tier II methodology (IPCC 2006; US EPA 2007), which is a function of the quantity of volatile solids excreted, CH_4 maximum potential production (0.24 m^3 per kg volatile solids) and a CH_4 conversion factor (21.7) for liquid systems.

$$MEF_j = (VS_j \times 365) \cdot (B_{0(j)} \times 0.67 \times \Sigma(MCF_{S,j} \times MS_{S,j})), \tag{4}$$

where MEF_j = manure management CH_4 emission factor (kg CH_4/animal.year), VS_j = daily excreted volatile solid (kg DM/animal.day) in Year *j*, 365 is the basis for calculating annual VS production (days/year), $B_{0(j)}$ is the maximum CH_4 producing capacity from manure produced (m^3 CH_4/kg DM of VS excreted) in Year *j*, $MCF_{S,j}$ = CH_4 conversion factors that reflect the proportion of VS actually converted to CH_4 compared with $B_{0(j)}$ (dimensionless) in manure-management System S and Year *j*, the factor 0.67 kg/m^3 is a conversion factor of m^3 CH_4 to kg CH_4, $MS_{S,j}$ is the fraction of manure handled using manure-management System S in Year *j* (dimensionless). The default values of VS, B_0 and MCF. for dairy cattle are provided in IPCC (2006). Due to lack of information, all manure was assumed to have been managed in the same way.

The total amount of CH_4 from manure MCH4j (kg/year) produced by the Mexican dairy cattle herd in Year j can be calculated as

$$MCH_{4j} = C_j \times MEF_j, \tag{5}$$

where C_j is the total number of dairy cows in Year j, and MEF_j is the corresponding annual CH_4 manure emission factor for Year j.

The prediction of the total amount of CH_4 produced by the Mexican dairy herd in Year j (TCH_{4j}, kg/year) is calculated as

$$TCH_{4j} = ECH_{4j} + MCH_{4j}. \tag{6}$$

Manure N_2O emissions were calculated as 0.001 kg of N_2O per kg of N excreted (IPCC 2006); however, the model did not include N_2O emissions from inorganic fertilisers. Carbon dioxide emissions from animal respiration were not considered due to CO_2 sequestration by plants in the photosynthesis process. Fuel CO_2 emissions from combustion were not included in the present study due to lack of data. The global warming potentials of CH_4 and N_2O were 25 and 298, respectively, on the basis of IPCC (2007) recommendations. Emissions from manure were then added to eneteric CH_4 emissions predicted by each model to obtain the total amount of GHG emitted per cow.

Results

In the past 40 years, the human population in Mexico has grown 133% and demand for milk 172%. Dairy production systems in the 1970s were pasture based, with forage to concentrate ratio (F : C) of 65 : 35. In contrast, in 2010 most dairy production systems use total mixed rations formulated to meet the cow's nutrient requirements (F : C ratio 40 : 60). Average milk yield has increased from 9.2 kg/day in 1970 to 14.9 kg/day in 2010. Feed conversion efficiency increased 32% (from 0.8 to 1.06 kg of milk/kg of DM intake) (Table 3).

Trends in enteric and manure CH_4 emissions in the years 1970 and 2010 are provided in Table 3, and Fig. 2 shows a comparison of ECH_4 with results obtained from COWPOLL model and IPCC-derived manure CH_4 estimates for the period1970–2010. Methane emissions estimated by the Moe and Tyrrell equation were 165 and 274 Gg per year for years 1970 and 2010, respectively. COWPOLL estimated 144 and 272 Gg of CH_4/year and the IPCC equation predicted 181 and 309 Gg of CH_4/year. All three models agreed that the highest emission estimates were in 2010. Regardless of the annual variation among models in absolute ECH_4 production, the

Table 3. Comparison of resource inputs, management and environmental impact of dairy production systems
DMI, DM intake; IPCC, Intergovernmental Panel on Climate Change

Variable	1970	2010	Difference (%)
Human population^A (millions)	48	112	133
Per capita consumption^B (mL/day)	222	260	17
Milk annual production^B (Mt)	3.91	10.6	172
Lactating cows^B (thousands)	1400	2351	68
Annual milk production^B (kg/cow)	2800	4541	62
Feed consumption^C (kg DMI/cow.day)	11.5	15.5	35
Total feed required (million t/year)	5.87	13.3	126
Efficiency (kg milk/kg DMI)	0.8	1.06	32
Total annual greenhouse gas emission (Mt/year)			
Methane^D	144	270	88
Nitrous oxide^E	0.349	0.713	104
Carbon dioxide equivalent^F	3704	6962	88
Emission by cow (kg/year)			
Methane^D	103	115	11
Nitrous oxide^E	0.249	0.303	22
Carbon dioxide equivalent^F	2649	2965	12
Emissions by litre of milk (g/L)			
Methane^D	36	25	–30
Nitrous oxide^E	0.089	0.067	–25
Carbon dioxide equivalent^F	926	645	–30

^{A}INEGI (2011).
^{B}FAO (2012).
^{C}Calculated with NRC (2001).
^{D}Methane emissions from enteric fermentation (COWPOLL) + manure (IPCC).
^{E}Nitrous oxide estimated with IPCC model.
^{F}Global warming potential, CH_4 = 25 (enteric CH_4 from COWPOLL model, and manure CH_4 from IPCC) and N_2O = 298 (from IPCC methodology).

overall trend was similar for all three models. Methane emissions increased particularly between 1996 and 2004 but decreased between 2005 and 2008. An interesting point was that although CH_4 emissions per cow increased 11%, CH_4 emissions per unit of milk decreased 30% (Table 3). Methane from manure fermentation ranged between 17.08 in 1970 and 28.6 Gg in 2010.

Trends in annual N_2O production are provided in Table 3 and Fig. 3. In the past 40 years, total N_2O emission increased 104%. Although N_2O emissions per cow increased (22%) in the same period, N_2O emissions per unit product decreased 25%. Nitrous oxide emissions showed a tendency to increase between 1970 and 1986, remained relatively constant from 1987 to 2008, and started to increase again between 2009 and 2010 (Fig. 3.).

Estimations of total GHGs are shown in Table 3 and Fig. 4. Trends of carbon footprint of Mexican dairy system (total GHG emissions in CO_2 equivalents) were similar to those of CH_4 emissions. All models showed that the highest emission estimates were in 2010. Carbon footprint per herd and per cow increased 88% and 12%, respectively, in the past 40 years; during the same time, emissions per unit product declined 30%. Using the Moe and Tyrrell equation, we estimated that total emissions from dairy population in Mexico increased from 1972 to 1990; decreased between 1991 and 1997 and then increased between 1998 and 2004. The COWPOLL model estimated total GHG emissions to increase from 1972 to 1984, decrease between 1985 and 1998, and then increase between 1999 and 2010. The IPCC model showed an increase from 1970 to 1984, a decrease between 1986 and 1996, followed by an increase between 1998 and 2004, a decrease between 2004 and 2006, and finally an increase between 2008 to 2010 (Fig. 4). In general, ECH_4 production was the highest source of emissions (85.3%), followed by CH_4 and N_2O from manure (11.5% and 3.2%, respectively).

Regardless of the models considered, the trend of carbon footprint was similar to that of CH_4 emissions because the majority of emissions came from ECH_4 (Fig. 5). A comparison of emissions (CO_2 equivalents) between models for the Year 2010 indicated 1.13% difference between Moe and Tyrrell and COWPOLL, 10% between Moe and Tyrrell and IPCC, and 11.1% between COWPOLL and IPCC.

Finally, a comparison between forecasted dairy production systems in Mexico and the US for the year 2020 is shown in Table 4. Data of the US system were based on Kebreab *et al.* (2008). If the efficiency of dairy production in Mexico increased at the same level as the US, fewer lactating cows would be required, and CH_4, N_2O and the carbon footprint would be reduced 38.8%, 75.6% and 39.4%, respectively, assuming constant demand for milk.

Discussion

In the past four decades, livestock production in Mexico has been growing; however, there is paucity of information regarding GHG emissions from cattle. On average, our estimates of ECH_4 emissions were 2.3%, 18.5% and 32.7% higher with COWPOLL, Moe and Tyrrell (Eqn 1) and IPCC Tier II (Eqn 2) models, respectively, than the latest available inventory for

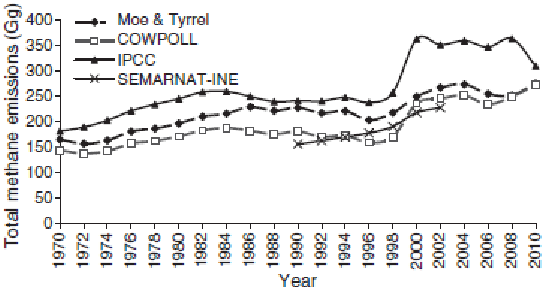

Fig. 2. Pattern of total methane (CH_4) emissions (enteric and manure CH_4). For the enteric CH_4 production for dairy cows, values are calculated using the equation of Moe and Tyrrell (1979), IPCC Tier II (IPCC 2006), and COWPOLL (Dijkstra *et al*. 1992) and five diets described in Table 2.

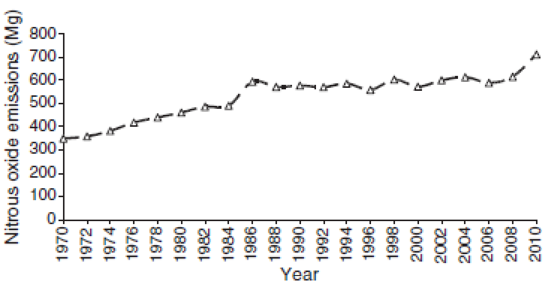

Fig. 3. Trends of nitrous oxide emissions from manure.

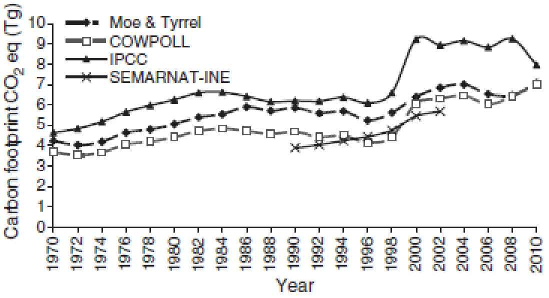

Fig. 4. Pattern of greenhouse gas emissions from enteric and manure fermentation (methane (CH_4) and nitrous oxide (N_2O)).

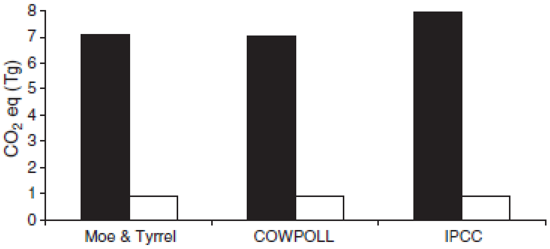

Fig. 5. Model comparison in estimates of enteric methane (black bars) and manure methane + nitrous oxide (white bars) emissions in 2010 in CO_2 equivalents.

Table 4. Comparison of the predicted environmental impact trend by dairy cattle to the year 2020, using current production systems from Mexico and USA

Trend of environmental impact according to the population size (115 762 289; CONAPO (2005) *per capita* consumption (260 mL/day = 11 billion kg of milk/year) and the current milk production system. USA data were calculated with dairy cattle characteristics from Kebreab *et al.* (2008)

Variable	Mexico	USA	Difference (%)
Milk production (kg/cow.day)	14.9[A]	33.1	122
Milk yield (kg/cow.year)	4541[A]	10095	122
Lactating cows (thousands)	2422	1089	–55.0
Feed (Mt)	37.4	26.7	–28.6
	GHG emission		
Methane (Mt)	278[B]	170	–38.8
Nitrous oxide (t)	734[B]	179[C]	–75.6
Carbon dioxide equivalent (Gt)	7.1[B]	4.3	–39.4

[A] FAO (2012).

[B] Values are taken from Table 3, using estimated data from 2010, where total CH_4 = 115 kg/animal.year, N_2O = 0.303 kg/animal.year, and CO_2 equivalent = 2965 kg/animal.year, and multiplied by animal population.

[C] Estimations were not realised in Kebreab *et al.* (2008). Manure N_2O emissions were estimated as 0.001 kg of N_2O per kg of N excreted (US EPA 2007). Nitrogen excretion by animal = 0.45 kg/day (ASABE 2005).

2002. Kebreab *et al.* (2008) compared mechanistic models such as COWPOLL and empirical models including IPCC and reported that mechanistic models were superior in their ability to predict CH_4 emissions. The authors reported that statistical models such as Tier II from IPCC tend to overestimate CH_4 emissions because CH_4 predictions depend on the amount of DM intake and do not respond to the types of nutrients supplied to the animals.

Other models for calculating GHG inventories have been developed by Ruiz-Suárez and González-Avalos (1997), but these authors included only enteric and manure CH_4 emissions from dairy and beef cattle. The authors modified IPCC Tier I model (EEF given for Mexican region) by calculating energy intake on the basis of bodyweight. Their estimates were not in agreement with our results; for example, in the year 1995, they estimated a CH_4 emission of 288 Gg for dairy cattle, which was 17.5%, 32.7%, and 69.4% more than the values we obtained in our study (with IPCC Tier II, Moe and Tyrrell and COWPOLL, respectively). These differences are likely due to models used (IPCC Tier I uses a fixed value) and also differences in the type of production system considered. Farming systems based on high-forage diets produce higher enteric emissions and lower milk yield per cow than do modern intensive systems (Haas *et al.* 2001; Hagemann *et al.* 2011).

The general trend observed in the present study was similar to that found for western Canada, which was heavily affected by cow numbers and improvement in milk production (Alemu *et al.* 2011). There was a downward trend in CH_4 emissions and carbon footprint during 1990–1998, most probably due to a decrease in cow numbers. Losada *et al.* (2000) reported such reduction to be due to national economic crisis and the high cost of production in the 1990s. For example, in the town of Tizayuca, Estado de Mexico, producers were forced to sell their herds or at least reduce the number of animals; however, after 1998, a tendency to increase the number of animal was ~15–20% per year, in the same area of Tizayuca.

In the current study, the higher CH_4 emissions and low milk yield per cow in the 1970s are attributed to more extensive systems with higher F : C ratio in the diet than in modern production systems, where intensification has been going on for at least two decades. Similar results have been described by Capper *et al.* (2009), who reported that an improvement in the management practices in intensive dairy production systems is an important way to reduce the environmental impact. This could be achieved through better crop yields, higher-quality feedstuffs, improvements in genetic and diet composition and greater milk yields (Boadi *et al.* 2004). This would then reduce GHG emissions and the number of cows required to produce a comparable amount of milk. Eastridge (2006) and LeBlanc *et al.* (2006) also pointed out that advances in dairy production in the past six decades have resulted in remarkable increases in production efficiency granted by genetic selection, ration formulation, preventative health programs, improved cows' performance and better management practices.

For a complete life-cycle analysis, data on, for example, fuel and electricity use, water consumption, crop and feedstuff production, land required, ration formulation, herd distribution and manure management will be required. Such a system-wide analysis will be able to assess GHG mitigation options to improve environmental sustainability of the Mexican livestock production system.

Conclusions

All three models used in the study were in agreement with the trend of emissions, which were generally rising as the years progressed but were heavily influenced when cow numbers changed during the study period. Enteric CH_4 emissions have been identified to be the major source of GHG emissions in Mexican livestock production systems; therefore, any mitigation strategy to reduce carbon footprint should include strategies to reduce enteric fermentation. Emission intensity is likely to decrease in the future as cow productivity and management practices are expected to follow trends similar to those in other North American countries. Any policy change to reduce emissions should use quantification methods that take into account diet composition and intake rather than fixed emission factors such those currently used in the Mexican national inventory.

Acknowledgements

This research was funded by CONACyT through a doctor of science scholarship (208836), UCMEXUS–CONACYT Collaborative Grants and Sesnon Endowed Chair fund (UC Davis).

References

Alemu AW, Dijkstra J, Bannink A, France J, Kebreab E (2011) Estimation of enteric methane emissions trends (1990–2008) from Manitoba beef cattle using empirical and mechanistic models. *Canadian Journal of Animal Science* **91**, 305–321. doi:10.4141/cjas2010-009

ASABE (2005) 'Manure production and characteristics. ASAE standard D384.2.' (American Society of Agricultural and Biological Engineers: St Joseph, MI)

Ayala QJ, Pinos-Rodríguez JM, Sabas-Pérez JG, Salinas-Pérez PS (2001) Perfil metabólico sanguíneo de vacas lecheras alimentadas con dietas conteniendo lasalocida y cultivos de levadura. *Investigación Agraria: Producción y Sanidad Animales* **16**, 143–152.

Baldwin RL (1995) 'Modeling ruminant digestion and metabolism.' (Chapman & Hall: London)

Boadi DA, Benchaar J, Chiquette J, Massé D (2004) Mitigation strategies to reduce enteric methane emissions from dairy cows. *Canadian Journal of Animal Science* **84**, 319–335. doi:10.4141/A03-109

Cabello FE, Román H, Pérez M (1971) Costos de producción de leche en bovinos Holstein-Friesan, Pardo Suizo y Jerzey en clima tropical. *Técnica Pecuaria en México* **15**, 5–8.

Capper JL, Castañeda-Gutiérrez E, Cady RA, Bauman DE (2008) The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. *Proceedings of the National Academy of Sciences, USA* **105**, 9668–9673. doi:10.1073/pnas.0802446105

Capper JL, Cady RA, Bauman DE (2009) The environmental impact of dairy production: 1944 compared with 2007. *Journal of Animal Science* **87**, 2160–2167. doi:10.2527/jas.2009-1781

CONAPO (2005) 'Proyecciones. De la población de México 2005–2050.' Consejo Nacional de Población. Available at http://www.conapo.gob.mx/index.php?option=com_content&view=article&id=36&Itemid=234 [Verified 20 June 2012].

Dijkstra J, Neal HD, Beever DE, France J (1992) Simulation of nutrient digestion, absortion and outflow in the rumen: model description. *The Journal of Nutrition* **122**, 2239–2256.

Eastridge ML (2006) Major advances in applied dairy nutrition. *Journal of Dairy Science* **89**, 1311–1323. doi:10.3168/jds.S0022-0302(06)72199-3

Espinoza OA, Macías AA, Valle MC, Chauvete M (2005) Los sistemas campesinos de producción de leche en el Estado de México. *Técnica Pecuaria en México* **43**, 39–56.

FAO (2012) 'Statistics. Food and Agriculture Organization of the United Nations.' Available at http://www.fao.org/corp/statistics/en/ [Verified 25 February 2012].

Haas G, Wetterich F, Köpke U (2001) Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. *Agriculture, Ecosystems & Environment* **83**, 43–53. doi:10.1016/S0167-8809(00)00160-2

Hagemann M, Hemme T, Ndambi A, Alqaisi O, Sultana MN (2011) Benchmarking of greenhouse gas emissions of bovine milk production systems for 38 countries. *Animal Feed Science and Technology* **166–167**, 46–58. doi:10.1016/j.anifeedsci.2011.04.002

INEGI (2011) 'Anuario estadistico por entidad federativa 2011.' (Instituto Nacional de Estadistica y Geografia: Aguascalientes, México)

IPCC (2006) 'Emissions from livestock and manure management. Agriculture, forestry and other land use.' (Intergovernmental Panel on Climate Change: Geneva, Switzerland)

IPCC (2007) 'Climatic change, 2007. The physical basis.' (Intergovernmental Panel on Climate Change: Geneva, Switzerland).

Kebreab E, Clark K, Wagner-Riddle C, France J (2006) Methane and nitrous oxide emissions from Canadian animal agriculture: a review. *Canadian Journal of Animal Science* **86**, 135–157. doi:10.4141/A05-010

Kebreab E, Johnson KA, Archibeque SL, Pape D, Wirth T (2008) Model for estimating enteric methane from United States dairy and feedlot cattle. *Journal of Animal Science* **86**, 2738–2748. doi:10.2527/jas.2008-0960

Le Du YLP, Baker RD, Barker JM (1976) Milk-fed calves. 2. The effect of lenght of milk feeding period and milk intake upon herbage intake and performance of grazing calves. *The Journal of Agricultural Science* **87**, 197–204. doi:10.1017/S0021859600026757

LeBlanc SJ, Lissemore KD, Kelton DF, Duffield TF, Leslie KE (2006) Major advances in disease prevention in dairy cattle. *Journal of Dairy Science* **89**, 1267–1279. doi:10.3168/jds.S0022-0302(06)72195-6

Losada H, Bennett R, Cortes J, Vieyra J, Soriano R (2000) The historical development of the Mexico City milk supply system: local and global contradictions. *Habitat International* **24**, 485–500. doi:10.1016/S0197-3975(00)00011-4

Mendoza-Martínez GG, González-Muñoz S, Riquelme-Villagrán E (1986) Efectos de la sustitución de sorgo por harina de yuca en raciones para vacas en lactancia. *Agrociencia* **64**, 127–131.

Mills JAN, Dijkstra A, Bannink A, Cammell SB, Kebreab E, France J (2001) A mechanistic model of whole-tract digestion and methanogenesis is the lactating dairy cow: model development, evaluation, and application. *Journal of Animal Science* **79**, 1584–1597.

Moe PW, Tyrrell HF (1979) Methane production in dairy cows. *Journal of Dairy Science* **62**, 1583–1586. doi:10.3168/jds.S0022-0302(79)83465-7

NRC (2001) 'Nutrient requirements of dairy cattle.' (National Academy Press: Washington, DC)

Pinos-Rodríguez JM, López S, Barcena R, Gonzalez-Muñoz SS, García JC, Jasso Y (2010) Effect of a polymer-coated urea based diet on the performance of lactating dairy cows. *Journal of Applied Animal Research* **37**, 201–205. doi:10.1080/09712119.2010.9707124

Plascencia-Jorquera A, Barreras-Serrano A, Avery-Zinn R (1999) Adición de grasa suplementaria en sustitución de forrajes en dietas para vacas en lactancia: digestión de nutrimentos y función ruminal. *Veterinaria (México)* **30**, 135–141.

Ruiz-Suárez LG, González-Avalos E (1997) Modeling methane emissions from cattle in México. *The Science of the Total Environment* **206**, 177–186.

SAGARPA (2010) 'Situación actual y perspectiva de la producción de leche de bovino en México 2010.' Claridades agropecuarias. Available at http://www.infoaserca.gob.mx/cla ridades/revistas/207/ca207–34.pdf [Verified 11 April 2011].

Saucedo MP (1984) 'Historia de la ganderία en México.' (UNAM: Distrito Federal, México)

SEMARNAT–INE (2002) 'Inventario nacional de gases de efecto invernadero 1990–2002.' Secretaria de Medio Ambiente y Recursos Naturales e Instituto Nacional de Ecología. Available at http://unfccc.int/ghg_data/items/3962.php [Verified 15 March 2012].

SIAP–SAGARPA (2008) Boletín de leche. Servicio de Información Agroalimentaria y Pesquera. Julio–Septiembre 2008. Available at http://www.siap.sagarpa.gob.mx [Verified 18 April 2011].

US EPA (2007) 'Inventory of US greenhouse gas emisions and sinks 1990–2005. Annex 3: methodological descriptions for additional source of sik categories.' (US Environmental Protection Agency: Washington, DC)

Weiss WP, Pinos-Rodríguez JM (2009) Production responses of dairy cows when fed supplemental fat in low-and high-forages diets. *Journal of Dairy Science* **92**, 6144–6155. doi:10.3168/jds.2009-2558

Capítulo III. Comparison of greenhouse gas emissions by intensive and semi-intensive dairy systems in México: an approach to Life Cycle Analysis (LCA)

Resumen general. Con el objetivo de comparar el impacto ambiental de sistemas estabulados de producción de leche con distintos grados de intensidad, se estimaron las emisiones de metano (entérico-estiércol), óxido nitroso (estiércol) y bióxido de carbono (uso de electricidad y quema de combustibles fósiles), eficiencia de producción, uso de recursos naturales como agua y suelo, y por último por la excreción de nutrientes en el estiércol. La diferenciación del grado de intensidad entre sistemas se realizó con un análisis multivariable cluster, donde las variables analizadas fueron, el número de animales en producción, el uso de combustibles fósiles y electricidad, el consumo de agua y el uso de suelo. Así, resultaron tres grados de intensidad (bajo, medio y alto). Siendo estos últimos los que mostraron ser más eficientes e impactar en menor medida al ambiente. La generación de metano entérico resulto la mayor fuente de gases de efecto invernadero. El manuscrito se enviará para su revisión a una revista indexada en el Journal Citation Reports.

Comparison of greenhouse gas emissions by intensive and semi-intensive dairy systems in México: an approach to Life Cycle Analysis (LCA)

Abstract

The objective of this study was to compare estimations of CH_4 (enteric-manure), N_2O (manure) and CO_2 (fuel and energy use) emissions in intensive and semi-intensive dairy farms in México, to compare the use of natural resources as water and soil, efficiency of production and excretion of nutrient in manure as N, P and K in these systems of milk production. Mechanical-Dynamic and empiric mathematical model were used to estimate greenhouse gas emissions in different type of intensive systems of milk production in Mexico. Three kinds of intensive systems were identified through a multivariable cluster analysis (low, medium and high). Feed efficiency kg milk per kg DMI was better in high intensive production systems. Enteric methane was identified as the major source of greenhouse gases in all type of intensity systems. High intensive dairies generated the lowest emissions of $CH_{4,}$ N_2O and CO_2 equivalent by unit of product, 18.6, 0.12 and 827.6 g, respectively. Thus, water footprint was lower in low intensive dairies 426.7 L of water/L of milk, cropland was highest in intensive systems but milk yield per area was better (30,938 kg/ha). Nutrient excretion N, P and K were lower in intensive dairies by unit of product, 13.2, 2.4 and 6.4 g. In conclusion, better feed efficiency decreases GHGs emissions, natural resources use and nutrient excretion by unit of product, Thus better manure management practices could mitigate carbon footprint as well.

Keywords: dairy intensive systems, milk production, environmental impact, methane

Introduction

In México, milk production is developed in technological, socioeconomic and agroecological heterogeneous conditions with four different kinds of systems: intensive, semi-intensive, familiar and double purpose (SIAP-SAGARPA, 2005). Livestock production is recognized to contribute significantly to emission of greenhouse gases (GHGs) mainly through emission of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Steinfeld *et al.*, 2006). In the last two decades, gas emissions by dairy cattle have been increased in 52% (Methane to Markets, 2008). Efficiency of production into systems is defined as the minimum quantity of inputs (feed, fossil fuels) and emissions of GHGs and nutrients in order to produce a considerable quantity of milk (Place and Mitloehner, 2010). The variety of milk production systems but mainly intensive systems make use of better nutritional feeds produced with inorganic and organic fertilizers (Smith, 1991), where in many scenarios losses of nutrient in manure (feces and urine) can occur, mainly; nitrogen, phosphorus and potassium, when they are present in excess all of them can have a negative impact in the environment (atmosphere, soil and water), human health and wild animals (Kojima *et al.*, 2005). Thus, milk production systems require other kind of inputs as fuels and electric energy, CO_2 is released from combustion of fossil fuels to power machinery, or electric energy generation (Pimentel and Pimentel, 1996; Rotz *et al.*, 2010). Gas measurements such as CH_4, N_2O and CO_2 are complex and require expensive equipment, one alternative has been the development and use of mathematical models to estimate greenhouse gas (GHG) emissions (Kebreab *et al.*, 2008). Mathematical models allow to predict the maximum amount of GHG production as CH_4 and N_2O by ruminants related to the intake of nutrients without perform costly experiments (Kebreab *et al.*, 2006).

At the same time, another concept that applies to animal production is the water footprint, which it is analogue to the ecological and the carbon footprint, but indicates fresh water use instead of land or fossil energy use and GHGs emissions (Hoekstra, 2003). Therefore the object of this study was 1) to compare estimations of CH_4 (enteric-manure), N_2O (manure) and CO_2 (fuel and energy use) emissions in intensive and semi-intensive dairy farms in México, 2) to collate the use of natural resources as water and soil, efficiency of production and through excretion of nutrient in manure as N, P and K in these systems of milk production.

Material and methods

Animal Care and Use Committee approval was not required by this study because any contact with the animals was not done.

A face-to-face, on-dairy questionnaire was conducted by the primary author (JARH). The same questionnaire was used on each dairy. Data on animal performance, diet composition, manure and soil samples from lactating, dry heifers and bulls, were collected from 26 dairy farms and Central and North of México (Queretaro, Jalisco, Guanajuato and Aguascalientes); ration and manure samples were kept frozen at -20 °C until they were analyzed. For feed and manure samples, analysis of dry matter contend, crude protein, NDF, ADF, fat and ash where done in order to fit the COWPOLL model and analyze nutrient losses, respectively.

Greenhouse gas emissions

Mathematical models

To estimate enteric fermentation, manure CH_4 and N_2O, a mechanistic COWPOLL (based on Dijkstra *et al*. 1992), and two empirical models (IPCC, 2006) were selected based on input data requirement, their ease of application, and widespread use to predict CH_4 and N_2O emissions and also their potential relevance to Mexican dairy production system.

As is described in Rendón-Huerta *et al.* (2013), enteric and manure CH_4 emissions were estimated with COWPOLL (Dijkstra *et al.*,1992) and IPCC (2006), respectively, and then they were sumarized. Manure N_2O emissions were calculated as 0.001 kg of N_2O per kg of N excreted (IPCC, 2006); however, the estimations did not include N_2O emissions from inorganic fertilizers. Carbon dioxide emissions from animal respiration were not considered due to CO_2 sequestration by plants in the photosynthesis process.

Carbon footprint

The global warming potential of CO_2, CH_4 and N_2O were 1, 25 and 298, respectively, on the basis of IPCC (2007) recommendations. Carbon dioxide from fuels and electric energy utilization were obtained through a questionnaire, where according with IPCC (2007) and the US EPA (2012), emissions by 1 kWh, 1 L gasoline and 1 L of diesel burned are equivalent to 0.73, 2.33 and 2.83 kg of CO_2.

Land, crops growing and hydric footprint

Land for pens, milk facility and cropland were asked in the questionnaire, main crops and yields per ha were asked as well.

Water consumption for irrigation crops, cleaning and drinking water from wells was calculated according to Bernoulli equation according with pumping time and seasons during the year.

$$Q = Av \qquad \text{Eq.[1]}$$

Where Q is the water flow rate in m^3/s, A is the pipe section area in m^2, and v is the average flux velocity in m/s (Mott, 1996).

Nutrient excretion

Efficiency of nitrogen (N), phosphorus (P) and potassium (K) utilization were analyzed in feed, and manure samples, through analysis of dry matter content, nitrogen, phosphorus and potassium.

Data Analysis

In order to classify between degrees of intensive confinement based livestock systems, a multivariable cluster analysis was made with the Cluster function of R Development Core Team, where variables as cow population, cropland, electricity use, fossil fuels and water consumption were used. Comparison of GHGs emissions, water footprint and nutrient excretion were analyzed with a completely randomized design through an analysis of variance (ANOVA). Comparison of GHG, milk production, DMI and efficiency of production were performance through a Pearson correlation. Finally the average scores were compared using the Tukey test ($p < 0.05$) (R Development Core Team, 2012).

Results and discussion

According with the Cluster analysis, three kind of intensive systems were identified as low, medium and high intensive, total populations including all categories of production into the system were 285, 588 and 1940 animals, respectively, where 128, 281 and 786 are lactating cows, respectively (Table 1). Highest milk yield values by cow per day was obtained in high intensive dairies compared with medium and low intensive dairies, 31.4, 29.6 and 25.9 kg, respectively (*P*=0.0014). Total milk production values per year were highest in high intensive systems compared to low intensive, 7610709 and 1058533 kg milk, respectively (*P*<0.0001). Efficiency was found highest as well in big dairies in contrast to small dairies, 1.31 and 1.07 kg milk/kg of DMI (*P*=0.0312). This effect is mainly due to the diet composition, where in high intensive dairies forage:concentrate ratio (F:C) average is 45:55 and in medium and low intensive dairies is in average 52:48 and 60:40, respectively. Silage corn and alfalfa were the main forage in diets, while commercial concentrate and corn (TMR) were in the concentrate proportion.

Greenhouse gas emissions

Greenhouse gases estimated in this trial were enteric CH_4, manure CH_4 and N_2O and CO_2 due to electric energy and fuels combustion (Table 2). Enteric methane estimation by total population is bigger in high intensive dairies followed by medium and low intensive dairies, 379380, 147589 and 70652 g/d (*P*<0.0001), statistical differences is due mainly to the herd size, same occurs in manure methane, manure nitrous oxide, carbon dioxide emissions for energy and fuel consumption, and finally in total carbon dioxide equivalent.

Estimated GHGs emissions by cow were significant in manure CH_4 (*P*<0.0001), highest values were obtained in low intensive systems compared to medium and high intensive systems, 55.4, 49.4 and 41 g/d, respectively. Enteric CH_4 emissions were not significantly different (P=0.8096), even if differences are not significant, enteric CH_4 was identified as the highest source of GHG in CO_2e followed by energy and fuels consumption. Results of total CH_4 by cow, are similar with those found by Aguerre *et al.* (2011), they point that cows fed with diets with forage-to-concentrate ratio equal to 47:53, produce a total of 538 g

CH_4/d and, such as forage ratio increases CH_4 emissions increases as well, this value is higher compared with those obtained in our study, but at the meantime same authors mention that their values in general are higher with those reported when measurements are done in chambers.

Emissions by unit of product (Table 2) were statistical significant in enteric CH_4, highest values were estimated in the low intensive dairy systems, followed by medium and high intensive dairy systems, 21.7, 18.6 and 15 g/L of milk, our results from intensive farms are similar with those found by Aguerre *et al.* (2011), they pointed out that diets with 47:53 forage-to-concentrate ratio and intake of 21 kg of DM, cows produce 14.0 g of CH_4/kg of milk, even if there is a difference in DMI between our study and their trial, main differences may be attributed to more crops variety in diet composition like extract soybean, roasted soybeans, etc. On the other hand, according with Hristov *et al.* (2013), there are some practices that could be reflected in increase milk production and as second benefit an enteric methane reduction, these practices are mainly, to improve forage quality, optimizing rumen function for higher microbial protein synthesis through feeding of a balanced diet.

Manure (Feces and urine) are mainly storage in solid between the farm and the croplands for months (4-6), and then spray in the field as fertilizer. Manure CH_4, and total CH_4 were statistical significant as well. Nitrous oxide estimations were highest in low intensive dairy systems 0.16 g/L of milk (P=0.0006). Even if high intensive systems use great quantity of energies (electric and fuels) in order to produce milk, emissions of CO_2 were highest in low intensive dairies compared to medium and high intensive dairies (P=0.0042). Finally total CO_2 equivalent (CO_2e) emissions by liter of milk were found significant different (P=0.0116), highest values were obtained in low intensive dairies, followed by medium and high intensive dairies, 1172, 833 and 827 g CO_2e/L of milk. Where CH_4 was the highest source of GHG, followed by energy and fuel consumption, these results agree with those found by Rotz el at. (2010). Thus, our results are quite similar to those reported by Hörtenhuber *et al.* (2010) ,found emissions up to the farm gate ranged from 0.90 to 1.17 kg CO_2e/kg milk, respectively. Phetteplace *et al.* (2001), pointed out that for a cow producing 7880 kg milk per year, carbon footprint was 1.09 kg CO_2e/kg of milk, respectively; another studies made by Capper *et al.* (2008), mention that a lactating cow producing 9050 kg of milk, generate 1.5 kg CO_2e/kg of milk, the difference between this last value and our values may be due that the farms that we visited do not produce the total feeds.

A Pearson correlation (Table 3), indicates that increasing efficiency of production (Milk kg/DMI kg), decreases CH_4, N_2O and CO_2 by unit of product (P= 0.0566, 0.0048, 0.0037, respectively).

Land, crops growing and hydric footprint

Area designated to growth crops and dairy facilities is showed in table 4, where low, medium and high intensive dairies presented 52, 114 and 246 ha, respectively. Main growing crops in the Spring-Summer cycle was corn, alfalfa sorghum, triticale and grasses, for the Autumn-Winter cycle oats is growth. Corn has the highest yield in tons/ha between crops, between systems, yield values were highest in high intensive dairies followed by medium and low intensive systems, 51, 58 and 61, respectively. Second crop with high yield was triticale, 17, 40 and 40 tons/ha for low, medium and high intensive systems, respectively. Alfalfa presented the lowest yield, 4 tons/ha each one without significant differences.

Consumption water for irrigation, cleaning and drink is presented in table 4. Highest use of water was done by high intensive systems, followed by medium and low intensive systems. Main water use is due to irrigation crops, then for drinking water and finally for cleaning (milk facility and pens that use flushing systems), it is important to mention that farms have permissions to extract water from subsoil at least 9 months a year or till the whole year. Water footprint did not present statistical differences by unit of product, our results showed that in order to produce one liter of milk, 426.7, 635.7 and 485.7 L of water are required in low, medium and high intensive systems, respectively. Our results show lower values compared with those made by Hoekstra and Chapagain (2007), worldwide water footprint per liter of milk is equivalent to 990 L of water; Thus, same authors mention that water required to produce one liter of milk in Mexico is about 2382 L, but they do not mention if calculations comes from an intensive Holstein dairy system or from a double purpose system (meat and milk production system) or both, which is important because, double purpose systems have very low milk production by cow, 4561 kg/cow/yr or 15 kg/d (Espinoza-Ortega *et al.,* 2005). The low water footprint got in this study must be due to that farms that were visited just produce around 40 to 50% of crops required in the diets, the rest have to be purchased or imported.

Nutrient excretion

Results of nutrient excretion are showed in table 5. Obviously nutrient excretion (nitrogen, phosphorus and potassium) in manure by total population were higher in intensive systems, due to they present the largest animal concentrations. When we look at nutrient excretion by animal, our results shows that animals whit higher concentrate ratio (high intensive dairies) excreted higher quantities of nitrogen compared to low concentrate ratio (low intensive dairies) 415.4 and 392 g/d, respectively (*P*=0.0014), but when we compared nitrogen excretion by unit of product, losses are lower in high intensive systems (13.2 g N/L of milk, *P*=0.0010); Our results are close to those found by Brito and Broderick (2006), they mention that with diets containing 51:50 forage-to-concentrate ratio, 25.4 kg of DMI and crude protein in percentage of 16.6, nitrogen excretion in manure is around 431 g N/d and 10.5 g N/L of milk. On the other hand, Groff and Wu (2005) found that when fed lactating cows with diets containing 50:50 forage-to-concentrate ratio, 16.25% CP and 24.7 kg of DMI, presents a nitrogen excretion of 484 g/cow and 13.5 g N/L of milk. Finally Hristov *et al.* (2004) mention that dairy cows fed with 48:52 forage-to-concentrate ratio, 15.8 % CP and 23.5 kg DMI, shows nitrogen losses in manure of 437 g/cow/d.

Results for phosphorus (P) excretion are present in Table 5. Highest values by cow were obtained in high intensive systems (74.9 g of P/d) compared with low and medium intensive systems (*P*=0.0021). But when phosphorus excretion are contrasted by unit of product, high intensive systems shows lower losses, 2.4 g/L of milk (*P*=0.0154). Our results are higher in contrast to those made by Weiss and Wyatt (2004) where they show that cows with DMI of 21 kg/d, milk yield of 30.4 kg/d and P intake of 79 g/d, presents a P excretion in manure of 47.7 g/d. Other studies with results similar to us, show excretion of phosphorus in manure about 59.3 g of P/d per cow when P intake was 84.8 g/d (Arriaga *et al*. 2009).

Finally results for potassium (K) excretion in manure are showed in Table 5. Highest values by cow were found in high intensive dairies compared with medium and low systems, 200.3, 197.6 and 192.1 g/d, respectively; these results agree with those found by Van Horn et al. (1994) and Nennich *et al.* (2005), for a lactating cow producing 31.8 and 31.4 kg of milk/d, K excretion is equal to 204 and 200 g/d, respectively; other studies made by Kojima *et al.* (2005) reported high K excretion (282 g/d) in cows producing 29.5 kg of milk/d.

Significant differences were found in K excretion to the environment by unit of product as well (*P*=0.0021), highest values were presented in low intensive dairies, 7.5 g/L of milk compared with high intensive dairies (6.4 g of K/L of milk). Cows in high intensive milk production systems made better use of potassium.

Conclusions

Low GHGs emissions were estimated lower by unit of product in high intensive dairy farms, mainly due to diet composition and efficiency of production. Enteric methane was identified as the major source of GHGs emissions; therefore any mitigation strategy to reduce carbon footprint specially in low intensive milk production systems, should be focused in reduce enteric methane through increasing efficiency of production; Second source of GHGs was energy consumption, manure management could be another practice to mitigate carbon footprint through anaerobic digesters in order to produce electric energy and low use of fertilizers on croplands, these practices could made a more sustainable production system. Emission intensity is likely to decrease in the future as cow productivity and management practices are expected to follow trends similar to those in intensive systems.

Acknowledgements

This research was funded by CONACYT through a doctor of science scholarship (208836) and by UC MEXUS-CONACYT Collaborative Grants. Authors also want to thank to the

Dr. Gustavo Tirado Estrada, M.V.Z. Juan Carlos Mora, Luis Ramón Saucedo Valenzuela and Jair Juárez for took us to the farms and to dairy farm owners for allow us take the samples and for gave us information.

References

Aguerre, M.J., M. A. Wattiaux, J. M. Powell, G. A. Broderick, and C. Arndt. 2011. Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. J. Dairy Sci. 94:3081–3093.

Arriaga, H., M. Pinto, S. Calsamiglia, and P. Merino. 2009. Nutritional and management strategies on nitrogen and phosphorus use efficiency of lactating dairy cattle on commercial farms: An environmental perspective. J. Dairy Sci. 92:204–215.

Brito, A. F. and G. A. Broderick. 2006. Effect of varying dietary ratios of alfalfa silage to corn silage on production and nitrogen utilization in lactating dairy cows. J. Dairy Sci. 89:3924–3938.

Capper, J. L., E. Castañeda-Gutíerrez, R. A. Cady, and D. E. Bauman. 2008. The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. Proc. Natl. Acad. Sci. USA 105:9668-9673.

Dijkstra J, H. D. Neal, D. E. Beever, and J. France. 1992. Simulation of nutrient digestion, absortion and outflow in the rumen: Model description. J. Nutr. 122:2239-2256.

Espinoza-Ortega, A., A. Álvarez-Macías, M. C. del Valle, M. Chauvete. 2005. La economía de los sistemas campesinos de producción de leche en el Estado de México. Tec. Pecu. Mex. 43(1):39-56.

Groff, E. B., and Z. Wu. 2005 Milk production and nitrogen excretion of dairy cows fed different amounts of protein and varying proportions of alfalfa and corn silage. J. Dairy Sci. 88:3619–3632.

Hoekstra, A.Y. 2003. *Virtual water trade:* Proceedings of the International Expert Meeting on Virtual Water Trade, UNESCO-IHE Value of water research report series, No 12, Delf, The Netherlands.

Hoekstra, A. Y., and A. K. Chapagain. 2007. Water footprints of nations: Water use by people as a fuction of their consumption pattern. Water Resour. Manag. 21(1):35-48.

Hörtenhuber, S., T. Lindenthal, B. Amon, T. Markut, L. Kirner, and W. Zollitsch. 2010. Greenhouse gas emissions from selected Austrian dairy production systems—model calculations considering the effects of land use change. Renew. Agr. Food Syst. 25(4):316-329.

Hristov, A. N., R. P. Etter, J. K. Ropp, and K. L. Grandeen. 2004. Effect of dietary crude protein level and degradability on ruminal fermentation and nitrogen utilization in lactating dairy cows. J. Anim. Sci. 82:3219–3229.

Hristov, A. N., J. Oh, J. L. Firkins, J. Dijkstra, E. Kebreab, G. Waghorn, H. P. S. Makkar, A. T. Adesogan, W. Yang, C. Lee, P. J. Gerber, B. Henderson, and J. M. Tricarico. 2013. SPECIAL TOPICS-Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. J. Anim. Sci. 91:5045–5069.

IPCC. 2006. Emissions from Livestock and manure management. Agriculture, Forestry and Other Land Use. Intergovernmental Panel on Climate Change. Geneva, Switzerland.

IPCC. 2007. Climate Change 2007: The Physical Basis. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Kebreab, E., K. Clark, C. Wagner-Riddle, and J. France. 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: A review. Can. J. Anim. Sci. 86:135-158.

Kebreab, E., K. A. Johnson, S. L. Archibeque, D. Pape, and T. Wirth. 2008. Model for estimating enteric methane from United States dairy and feedlot cattle. J. Anim. Sci. 86:2738-2748.

Kojima, H., S. Kume, K. Nonaka, T. Oshita, T. Kozakai, and H. Hirooka. 2005. Effects of feeding and animal performance on nitrogen, phosphorus and potassium excretion by Holstein cows. Anim. Sci. J. 76:139-145.

Methane to Markets, 2008. Mexico Profile. Animal Waste Management Emissions. Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT) and Agency for the International Development of the Unite States (USAID). 41 pp. http://www.methanetomarkets.org/documents/ag_cap_mexico.pdf

Mott, L. R. 1996. Applied fluid mechanics. Fourth ed., Prentice Hall Inc. New York, USA.

Nennich, T. D., J. H. Harrison, L. M. VanWieringen, D. Meyer, A. J. Heinrichs, W. P. Weiss, N. R. St-Pierre, R. L. Kincaid, D. L. Davidson, and E. Block. 2005. Prediction of manure and nutrient excretion from dairy cattle. J. Dairy Sci. 88:3721–3733.

Phetteplace, H. W., D. E. Johnson, and A. F. Seidl. 2001. Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States. Nutr. Cycl. Agroecosyst. 60:99–102.

Pimentel, D., and M. Pimentel. 1996. Energy use in livestock production. In: Food Energy, and Society. Pimentel D. and M. Pimentel (eds). University Press of Colorado. Niwot, CO, USA.

Place, S. E., and F. M. Mitloehner. 2010. Contemporary environmental issues: A review of the dairy industry´s role in climate change and air quality and the potential of mitigation through improved production efficiency. J. Dairy Sci. 93: 3407-3416.

R Development Core Team. 2012. R: A Language and Environement for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. URL http://www.R-project.org/.

Rendón-Huerta J. A., J. M. Pinos-Rodríguez, J. C. García-López, L. G. Yáñez-Estrada, and E. Kebreab. 2013. Trends in greenhouse gas emissions from dairy cattle in Mexico between 1970 and 2010. Anim. Prod. Sci. http://dx.doi.org/10.1071/AN12327

Rotz, C. A., F. Montes, and D. S. Chianese. 2010. The carbon footprint of dairy production systems through partial life cycle assessment. J. Dairy Sci. 93:1266-1282.

SIAP-SAGARPA. 2005. Producción nacional de leche. Servicio de Información Agroalimentaria y Pesquera-Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación [Online]. Available at: http://w4.siap.gob.mx/sispro/portales/pecuarios/lechebovino/situacion/descripcion.pdf (verified 18 April 2013).

Smith, L. W. 1991. Production systems. In: Handbook of animal science. Putmnam P. A. (ed). Academic Press. USA. p. 279-291.

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. De Haan. 2006. Livestock's Long Shadow: Environmental Issues and Options. Rome, Italy: Food and Agriculture Organization.

US EPA. 2012. Calculations and references: Electricity Reductions (kilowatt-hours). US Environmental Protection Agency. http://www.epa.gov/cleanenergy/energy-resources/refs.html. (verified 18 April 2013).

Van Horn, H. H., A. C. Wilkie, W. J. Powers, and R. A. Nordstedt. 1994. Components of dairy manure management systems. J. Dairy Sci. 77:2008–2030.

Weiss, W. P., and D. J. Wyatt. 2004. Macromineral digestion by lactating dairy cows: Estimating phosphorus excretion via manure. J. Dairy Sci. 87:2158–2166.

Table 1. Animal population distribution by category and milk production in three different intensive systems

	Level of intensification				
	Low intensive	Medium intensive	High intensive	SEM	*P*-value
Category					
Early lactation cows	115	237	590	29.2	<0.0001
Midlactation cows	15	35	154	46.7	0.0181
Late lactation cows	4	9	42	16.5	0.3636
Dry cows	28	38	135	16.8	0.0012
Heifers	88	153	400	9.17	<0.0001
Calves	43	93	589	55.8	0.0002
Bulls	2	23	31	23.8	0.2679
Total	295	588	1941	67.5	<0.0001
Milk yield, kg/cow.d	25.9	29.6	31.4	1.05	0.0014
Milk yield, kg/cow.yr × 10^3	7.89	9.02	9.57	0.31	0.0016
Total milk production, kg/yr × 10^6	1.05	2.53	7.52	0.49	<0.0001
DMI, kg/d	24.1	23.2	23.9	0.84	0.9764
Efficiency, kg milk /kg DMI	1.07	1.27	1.31	0.05	0.0312

SEM= Standard error of the mean.

Table 2. Greenhouse gas emissions by three different intensive systems

	Low intensive	Medium intensive	High intensive	SEM	*P*-value
Total cows	285	588	1940	136	<0.0001
Lactating cows	134	281	786	51	<0.0001
Total milk production, kg/d	3470.6	8317.6	24680	1197	<0.0001
GHG emissions from whole system, g/d					
Enteric $CH_4 \times 10^3$	70.6	147.5	379.3	20.3	<0.0001
Manure $CH_4 \times 10^3$	15.8	29	79.5	4.8	<0.0001
Total $CH_4 \times 10^3$	86.4	176.6	458.9	25	<0.0001
Manure $N_2O \times 10^3$	0.56	1.01	3.05	0.18	<0.0001
Energy & Fuel CO_2 eq $\times 10^6$	1.74	2.22	8.06	0.19	<0.0001
Total CO_2 eq $\times 10^6$	4.07	6.93	20.45	0.76	0.0002
GHG emissions for lactating cow, g/d					
Enteric CH_4	469	459	456	12.3	0.8096
Manure CH_4	55.4	49.4	41	2.3	<0.0001
Total CH_4	524.4	507.4	497	4.3	<0.0001
Manure N_2O	4.21	5.38	3.83	0.77	0.5264
Energy & Fuel CO_2 eq $\times 10^3$	8.29	5.70	6.13	1.38	0.4297
Total CO_2 eq $\times 10^3$	22.6	19.9	19.7	4.4	0.6343
¥*GHG emissions for unit product, g/L*					
Enteric CH_4	20.4	17.7	15.4	1.35	0.0112
Manure CH_4	4.5	3.5	3.2	0.28	0.0007

Total CH_4	24.9	21.2	18.6	1.80	0.0068
Manure N_2O	0.16	0.12	0.12	0.008	0.0006
Energy & Fuel CO_2 eq	501.7	267	327	55.3	0.1142
Total CO_2 eq	1172	833	827.6	77.3	0.0116

[¥] Include the whole system

SEM= Standard error of the mean.

Table 3. Significant (*P* < 0.05) Pearson correlation coefficients for efficiency, lactating cows, milk production and GHG

	Efficiency	Lactating cows	Milk production/d
Efficiency	1.00000	0.38284	0.47965
		0.0648	0.0177
Lactating cows	0.38284	1.00000	0.95148
	0.0648		<.0001
Dairy milk production	0.47965	0.95148	1.00000
	0.0177	<.0001	
CH_4 per cow	0.06270	-0.19864	-0.04914
	0.7710	0.3521	0.8196
N_2O per cow	0.18762	-0.25656	-0.06442
	0.3800	0.2262	0.7649
CO_2 per cow	0.07249	-0.35132	-0.14806
	0.7364	0.0923	0.4899
CH_4 per L of milk	-0.39429	-0.58271	-0.59812
	0.0566	0.0028	0.0020
N_2O per L of milk	-0.55534	-0.57879	-0.64581
	0.0048	0.0030	0.0007
CO_2 per L of milk	-0.56895	-0.53776	-0.55525
	0.0037	0.0067	0.0049

Table 4. Energy, land, and water use for growing crops in three different intensive systems

	Less intensive	Medium intensive	High intensive	SEM	*P*-value
Electricity[±], kWh/mo × 10^3	64.9	81.1	288.1	13	<0.0001
Gasoline, L/mo × 10^3	0.413	0.712	2.029	0.18	0.0036
Diesel, L/mo × 10^3	1.36	2.26	9.88	1.70	0.0119
Area for growing crops, milk facility and pens					
Land, ha	52	114	246	21.2	<0.0001
Milk yield, kg/ha × 10^3	19.6	25.6	30.9	4.49	0.0054
Main crops, yield (tons/ha)					
Corn	51	58	61		
Alfalfa	4	4	4		
Triticale	37	40	40		
Oats	10	23	15		
Barley	-	-	8		
Sorghum	6	8	-		
Wheat	-	-	2		
Grass	-	32	30		
Water, L/yr × 10^9	0.41	1.63	3.40	0.21	<0.0001
Water, L/L of milk	426.7	635.7	485.7	78	0.2446

[±] Electricity for the dairy facility and for irrigation (water pumps), - crops are not growing in these systems, SEM = Standard error of the mean.

Table 5. Nutrient excretion in manure by total system population, cow and unit of product

Issue	Less intensive	Medium intensive	High intensive	SEM	*P*-value
Nutrient excretion by total population, g/d					
Nitrogen	52926	115155	327475	19709	<0.0001
Phosphorus	6110	14190	43151	3560	<0.0001
Potassium	25887	55732	157806	9415	<0.0001
Nutrient excretion by cow, g/d					
Nitrogen	392	407.5	415.4	3.63	0.0014
Phosphorus	70.6	73.5	74.9	0.68	0.0021
Potassium	192	197.6	200.3	1.28	0.0016
Nutrient excretion by unit product, g/d					
Nitrogen	15.2	13.9	13.2	0.32	0.0010
Phosphorus	2.74	2.5	2.4	0.05	0.0054
Potassium	7.5	6.7	6.4	0.03	0.0021

SEM= Standard error of the mean.

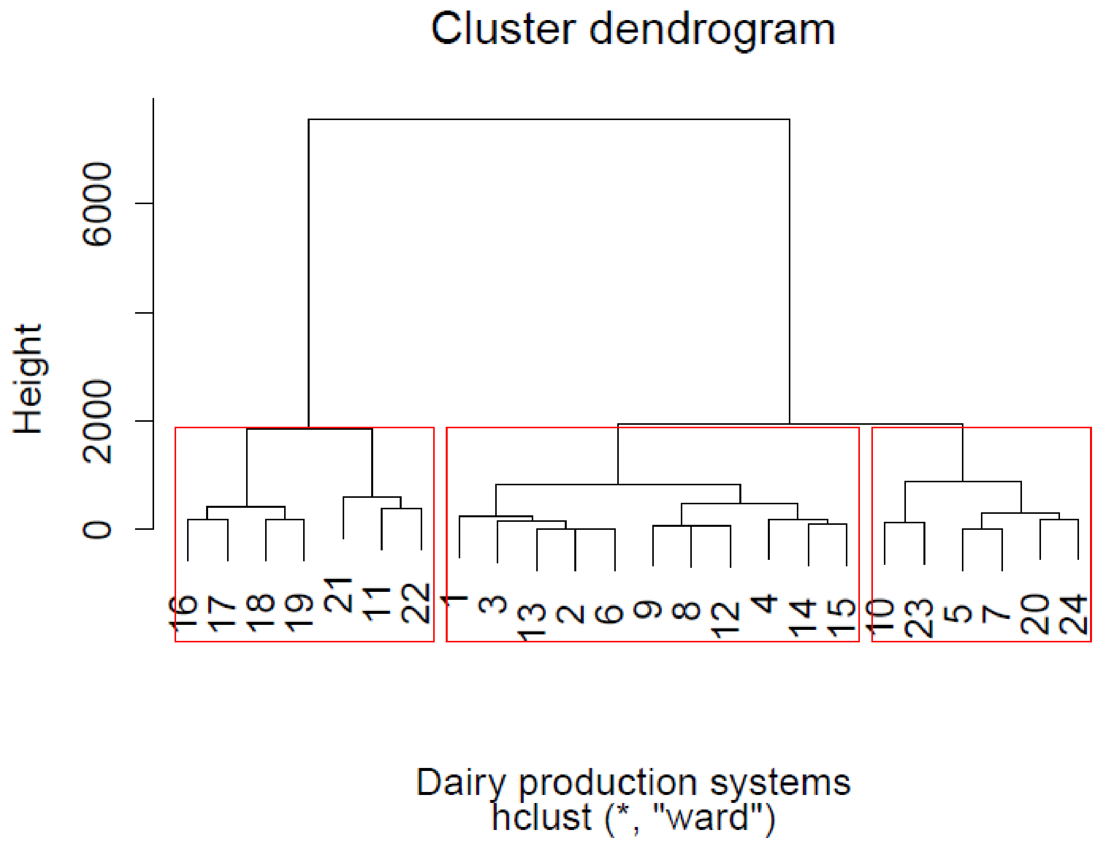

Figure 1. Schematic distribution of dairies by type of production intensity derived from the multivariable cluster analysis.

Capítulo IV. Feasibility and Environmental Impact of Generating Electricity with Solar Panels and Anaerobic Digesters in Dairies

Resumen General. Con el objetivo de evaluar la rentabilidad y el impacto ambiental producido por paneles solares y digestores anaerobios en establos lecheros, se realizó una simulación con un fermentador tipo laguna y un motogenerador de 60 kWh, además de paneles solares de 10.34 kWh con establos de entre 300 y 1600 vacas lecheras. La generación máxima de electricidad estimada (combinando los dos tipos) fue de 52937 kW para establos pequeños (de 300 a 500 vacas) y de 208998 kW para establos grandes (de 1150 a 1600 vacas) al bimestre, disminuyendo el consumo directo a la CFE en 66,4% y en el impacto ambiental del 63%. La amortización estimada osciló entre US$ 2642 y US$ 10316 al bimestre para establos pequeños y grandes, respectivamente; recuperándose la inversión en un plazo de 11 años para establos pequeños y de 5 para establos grandes y de 10 o 4 años, si se toma en cuenta la venta de bonos de carbono. El manuscrito se envió a la *Journal of Sustainable Agriculture* (ISSN: 1044-0046) para su revisión.

Feasibility and Environmental Impact of Generating Electricity with Solar Panels and Anaerobic Digesters in Dairies

Juan Antonio Rendón-Huerta[a], Juan Manuel Pinos-Rodríguez[b], Héctor Martín Duran-García[c] Leticia Yañez-Estrada[d], Juan Carlos García López[c],

[a]Programa Multidisciplinario de Posgrado en Ciencias Ambientales, Universidad Autónoma de San Luis Potosí. Avenida Manuel Nava # 201, Zona Universitaria, C.P. 7829, San Luis Potosí, México. jrendonhuerta@hotmail.com

[b]Centro de Biociencias, UASLP. Carretera San Luis Potosí-Matehuala km 14.5, Ejido Palma de la Cruz, Soledad de Graciano Sánchez C.P. 78321, San Luis Potosí, México.

[c]Instituto de Investigación de Zonas Desérticas, UASLP. Altair # 200, Fraccionamiento del Llano, C.P. 78377, San Luis Potosí, México.

[d]Departamento de Toxicología Ambiental, Facultad de Medicina, UASLP, Avenida Manuel Nava 201, Zona Universitaria, 78290, San Luis Potosí, Mexico.

Abstract

This study was conducted to simulate the feasibility and environmental impact of solar panels and anaerobic digesters in dairies. The study included dairies with 300-1600 cows, considering a maximum daily methane generation of 156 g CH_4/cow under anaerobic conditions of a covered lagoon digester with a 60 kWh motor generator and 10,34 kWh solar panels. Maximum bi-monthly generation of electricity (combining the two types of alternative sources) would be 52937 kW for small dairies (300-400 cows) and 208998 kW for large dairies (1150-1600 cows). This would reduce direct consumption of electricity produced by the CFE by 66,4 % and environmental impact by 63 %. Estimated amortization oscillated between US$ 2642 and US$ 10316 bi-monthly for small and large dairies, respectively, allowing recovery of the investment over a period of 11 years for small dairies and 5 years for large dairies. If sale of carbon bonds is taken into account, this time would be reduced 10 or 4 years.

Key words: Alternative energy for dairies, clean energy, environmental impact, bioenergy, digesters.

Introduction

Large quantities of organic waste are generated in dairies by stabled cows (Dungan 2010). These wastes, mainly manure, can be economically and environmentally beneficial when treated in anaerobic fermenters to produce biogas for fueling electric generators (Lansing et al. 2010). Anaerobic fermentation of manure is a biochemical process in which microorganisms (archea) breakdown organic matter and produce flammable gas, mainly methane (CH_4) (Sanders et al. 2010; Montes et al. 2013) as well as other gases as by-products (Table 1). It has been demonstrated that methane is able to absorb 25 times more heat than CO_2 (IPCC 2007). When CH_4 is collected and used as an energy source, it can substitute combusted fossil fuels reducing emissions of greenhouse gases (GHG), hydrocarbons, and particulate matter (Börjesson and Berglund 2006). In recent years several Mexican government organs have shown interest in reducing GHG generated by hog farms and dairies through adoption of technology for producing electricity and reducing costs (FIRCO-SAGARPA 2012). According to FIRCO-SAGARPA, by 2009 there were 142 manure fermentation systems, of which 54 are located in dairies and the rest are on hog farms. Also sunlight is converted to electric energy by solar panels. These technologies, also called clean energy, require capital investment with long term recovery. The objective of this study was to simulate the feasibility of generating electric energy combining solar panels and fermenters for generating electricity and their environmental impact in dairies.

Methodology

The feasibility study on generation of electric energy in dairy stables was conducted with information collected with a survey of ten dairy ranches. The objective of the questionnaires was to determine herd size and composition by productive stage as well as production and management of manure and consumption of electric energy for dairy operation. The factor of methane production from manure was calculated with the method proposed for different categories of animals by the Intergovernmental Panel on Climate Change, tier II (IPCC 2006). This is in function of the amount of volatile excreted solids, maximum potential for methane production equal to 0,24 m^3 per kg of volatile solids, and a methane conversion factor of 78 and 4 % for anaerobic and aerobic systems, respectively (equation 1).

$$FE = (SV_j)\cdot(B_{0(j)}\times 0{,}67\times (MCF_{S,j}\times MS_{S,j})) \qquad [1]$$

Where FE = daily factor of CH_4 emission of the livestock population, kg CH_4/animal/day; SV = volatile solids excreted per day, kg dry matter/animal/day; Bo = maximum capacity for methane production of the produced manure, m^3 CH_4 /kg SV excreted; 0,67 = conversion factor of m^3 CH_4 to kg CH_4; MCF = methane conversion factor for each manure management system S by climate region, %; MS = fraction of livestock manure managed under the system of waste management in the climate region, without dimension. The values of SV, Bo and MCF for dairy cattle were taken from the IPCC guide (2006) and the American Society of Agricultural Engineers (ASAE 2005) (Table 2).

Once the maximum methane production in a covered lagoon digester (Figure 1) was calculated, generation of electric energy was calculated for a reference generator Econogas™ biogas 60 in kW and power factor of 0,8 (www.mopesa.com.mx). CO_2 emissions (Equation 2) were also estimated from the methane combustion chemical formula (Brown et al. 2003).

$$CH_{4(g)} + 2\ O_2 \rightarrow CO_{2(g)} + 2\ H_2O \qquad [2]$$

To determine generation of electric energy by solar panels with connection to the power line network, technological data from ERDM Solar (http://www.edrm-solar.com) were used. Maximum power generation is 10,34 kWh. Later, the maximum electric power production was estimated based on average daily insolation in the study area (NMSU 1999).

Also, daily CO_2 equivalent emissions (CO_2 eq) with and without use of alternative energy were compared, where generation of N_2O, according to IPCC, is reduced to zero under anaerobic conditions or as 0.001 kg of N_2O per kg of N excreted in aerobic conditions (IPCC 2006). Carbon dioxide from electric energy utilization according to IPCC (2007) and Cai et al. (2013) emissions for 1 kWh is equivalent to 0,73 kg of CO_2. The global warming potentials (GWP) of CO_2, CH_4 and N_2O were 1, 25 and 298, respectively, based on IPCC (2007) recommendations.

Finally, the feasibility analysis included cost analysis of starting up the two types of alternative energy, anaerobic digesters and solar panels, and their associated benefits in dairy stables connected to the Federal Commission of Electricity (CFE) power lines; the price is US$ 0,18 per kWh (CFE 2013).

For the descriptive statistical analysis, the dairies were grouped by herd size, since management practices were similar, to facilitate simulation. Four size categories resulted: 300-500; 600-750; 800-1000 and 1150-1600 cows. For the economic and financial study, the following was taken into account: 1) bi-monthly energy demand, that is, energy consumption in the dairy installations (milking room, office and corral lighting, water pumps), 2) investment in fixed actives, and 3) difference between electricity consumed from the CFE network with and without the use of biogas and solar panels.

Results and Discussion

According to the Fideicomiso Instituido de Riesgo Compartido (FIRCO-Instituted Shared Risk Fund), support for acquisition of fermenters and generators for converting organic wastes into electricity is granted in areas with greater concentrations of animals (more than 300 animals for milk-producing ranches), where manure management facilitates production of biogas and installation of the fermenter does not affect bio-safety of the dairy (FIRCO-SAGARPA 2013). Aid for acquiring a motor generator is justified if the production unit has a monthly demand above 10000 kWh.

Investment in the construction of a covered lagoon digester, acquisition of an electric generator and solar panels is approximately US$ 150107,5 (Table 3). It should be mentioned that there is aid from SAGARPA (Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación- Ministry of Agriculture, Livestock, Rural Development, Fishing and Food) through FIRCO of up to US$ 76923,10 to buy fermenters with the aim of sustainable management of organic wastes in dairy stables. Moreover, aid of up to US$ 19230,70 is offered for acquisition of electric generators with capacity to generate 60 kWh (Milenio 2011; ASERCA 2007) and of up to 50 % of the cost of solar panels whose total cost is no more than US$ 307692,30 (ASERCA 2008). It is important to mention that for this type of technology to function, the cooperation of government programs and other organizations is needed to obtain environmental and economic benefits (Bond and Templeton 2011; Wang et al. 2011).

The study of feasibility of acquiring alternative energy, also called “mechanism of clean development” is represented in Figure 2. Here, it is estimated that the investment is recovered over a period of approximately 11 years in small dairies (300-500 cows) and 5 years in large dairies (1150-1600 cows), under the assumption that herd size and consumption of electricity do not change during this period. Bi-monthly amortization calculated with the generation of alternative energy sources was estimated at US$ 2642 and US$ 10316 for small and large dairies, respectively. Moreover, reduction of GHG in the stables could be sold to other regions or countries that emit quantities of GHG above those established by the Kyoto Protocol, through so-called certificates of emissions reduction (CER) or carbon bonds promoted by World Bank (ECOFYS 2013). In California, USA, these bonds have a cost of US$10/$tCO_2$ equivalent (tCO_2 eq). We calculate that with the use of alternative energy sources, GHG emissions would decrease bi-monthly by between 41,4 and 91,2 tCO_2 equivalent. Selling bonds could thus increase incomes by US$ 414 and US$

912 for small and large dairies, respectively. Together with the savings in energy, the new period of amortization is estimated at 10 years for small dairies and 4 for large (Figure 2).

Total electric energy consumption from CFE was on average 121945 and 356565 kW bi-monthly in small and large dairies, respectively. The maximum amount of electricity produced by using CH_4 as fuel is on average 965 and 3069 kW/d in small and large dairies, respectively, while solar panels generate an average of 57,9 kW/d in this region that has 4,3 kWh/m^2 insolation in December and 6,9 kWh/m^2 in May, reaching a production of 44,4 kW/d and 71,3 kW/d, respectively. Combining the two forms of generating electric energy could achieve a production of 368431 and 1141318,5 kW/year, coinciding with other studies (Casas-Prieto et al. 2009; Rivas-Lucero et al. 2012) in which a maximum of 353429 and 1325350 kW per year is produced in dairies with 300-500 and 1500 cows, like our classification of small and large dairies.

Emissions of CO_2 equivalent were compared with traditional use of electricity from the CFE network and with open-air management of manure. Use of the combination fermenters and solar panels resulted in 61 % lower emissions. According to Dhingra et al. (2011), this type of digester reduced GHG emissions from 23 to 53% when compared with households without biogas, depending on the condition of the digester, technical assistance, and operator ability. The total CO_2 equivalent estimated in dairies without the use of electricity generating technologies was 3733 kg/d CO_2 equivalent, 62 %, 17,7 % and 20,3 %, corresponding to consumption of electricity, CH_4 and N_2O, respectively. With the use of alternative sources of energy, total emissions of CO_2 equivalent was estimated at 1472 kg/d, of which 88,3 % was electricity used and 11,7 % to fuel the motor transformer (Figure 3).

Other studies have shown that use of prickly pear cladodes can increase biogas generation in fermenters to more than 70 % methane when mixed in a 3:1 proportion of prickly pear to cattle manure (Méndez-Gallegos et al. 2010). Moreover, prolonged anaerobic digestion of manure in anaerobic digesters decreases odors up to 91 % by decreasing the concentration of the chemical oxygen demand (Van Horn et al. 1994; Massé et al. 2010), especially those produced in places with temperatures above 25 ºC. Moreover, application of digester effluent, commonly called digestate, on crop field soil increases organic matter content (Dungan 2010), favors soil segregate formation, improves water infiltration and helps eliminate pathogenic microorganisms from the effluent (Massé et al. 2010).

Generation and burning of methane leads to emission of nitrogen oxide (NOx) because biogas contains ammonium (NH_3), which when burned produces NOx (Burch and Southward 2001). McCarty (2000) proposes the use of catalyzers in CH_4, among which he highlights platinum and palladium oxide. Their use, however, could increase initial investment.

Conclusions

With the sale of certificates of emissions reduction (CERs), dairies with more than 1600 cows in production can reduce the amortization period of their investment in implementation of alternative energy sources in stabled dairy ranches.

The use of alternative energy sources is an option for contributing to mitigate the greenhouse effect by putting organic matter decomposition and sunlight to use generating electricity for dairies.

Once the investment is amortized, operation costs of the dairies decrease by producing the electricity consumed and by using the manure.

Acknowledgements

That work was funded by CONACYT through a grant awarded to Juan Antonio Rendón Huerta (208836) and UCMEXUS-CONACYT Collaborative Grants.

References

Abbasi, T., Tauseef, S.M., and Abbasi, S.A. 2012. *Biogas Energy*, New York, USA: Springer

AgSTAR. 2011. *AD 101 Biogas recovery systems. US EPA*. http://www.epa.gov/agstar/anaerobic/ad101/index.html. (accessed 02 May 2013).

ASAE. 2005. *Manure production and characteristics*. ASAE Standard D384.2 MAR2005. American Society of Agricultural Engineers. St. Joseph, MI, USA.

ASERCA. 2007. La energía renovable en el sector agropecuario, una alternativa para el desarrollo sustentable. *Revista Claridades Agropecuarias*. 167: 3-44.

ASERCA. 2008. Sistemas fotovoltaicos para el bombeo de agua, una alternativa para el aprovechamiento de la energía solar en el sector agropecuario. *Revista Claridades Agropecuarias*. 173: 3-25.

BANXICO. 2013. *Mercado cambiario (Tipos de cambio)*. http://www.banxico.org.mx/portal-mercado-cambiario/. (accessed 14 June2013).

Bond, T., and Templeton, M.R. 2011. History and future of domestic biogas plants in the developing world. *Energy for Sustainable Development* 15:347–354.

Börjesson, P., and Berglund, M. 2006. Environmental systems analysis of biogas systems – Part 1: Fuel-cycle emissions. *Biomass Bioenergy* 30:469–485.

Brown, T.L., LeMay, H.E., Bursten, B.E., and Burdge, J.R. 2003. *Chemistry the central science*, 9th ed, New Jersey, USA: Prentice Hall.

Burch, R., and Southward, B.W.L. 2001. The nature of the active metal surface of catalysts for the clean combustion of biogas containing ammonia. *Journal of Catalysis* 198(2): 286-295.

Cai, H., Wang, M., Elgowainy, A., and Han, J. 2013. *Updated Greenhouse Gas and Criteria Air Pollutant Emission Factors of the U.S. Electric Generating Units in 2010*. http://greet.es.anl.gov/publication-electricity-13. (accessed 05 November 2013).

Casas-Prieto, M.A., Rivas-Lucero, B.A., Soto-Zapata, M., Segovia-Lerma, A., Morales-Morales, H.A., Cuevas-González, M.I., and Keissling-Davison, C.M. 2009. Estudio de factibilidad para la puesta en marcha de los digestores anaeróbicos en establos lecheros en la cuenca de Delicias, Chih. *Revista Mexicana de Agronegocios* 8(24):745-756.

CFE. 2013. *Tarifas generales en alta tensión. Comisión Federal de Electricidad.* http://app.cfe.gob.mx/Aplicaciones/CCFE/Tarifas/Tarifas/tarifas_negocio.asp. (accessed 02 May 2013).

Dhingra, R., Christensen, E., Liu, Y., Zhong, B., Fu, C., Yost, M., and Remains, J. 2011. Greenhouse gas emission reductions from domestic anaerobic digesters linked with sustainable sanitation in rural China. *Environmental Science and Technology* 45:2345–2352.

Dungan, R.S. 2010. BOARD-INVITED REVIEW: Fate and transport of bioaerosols associated with livestock operation and manures. *Journal of Animal Science* 88:3693-3706.

ECOFYS. 2013. Mapping carbon pricing initiatives developments and prospects. Carbon Finance at the World Bank. Washington DC, USA.

Finanzas Carbono. 2013. *Noticias. Agricultores y ganaderos de la Laguna (México) van por la energía solar, instalarán sistemas fotovoltaicos.* http://finanzascarbono.org/noticias_externas/agricultores-y-ganaderos-de-la-laguna-mexico-van-por-la-energia-solar-instalaran-sistemas-fotovoltaicos/. (accessed 26 May 2013).

FIRCO-SAGARPA. 2012. *Criterios de elegibilidad*. http://www.firco.gob.mx/proyectos/provar/Paginas/provar_2.aspx. (accessed 24 April 2013).

FIRCO-SAGARPA. 2013. *Programa de sustentabilidad de os recursos naturales bioenergía y fuentes alternativas 2013*. http:// www.firco.gob.mx/Componentes 2013/bioenergia_2013/Paginas/bioenergia.aspx. (accessed 07 September 2013).

IPCC. 2006. Emissions from Livestock and manure management. Agriculture, Forestry and Other Land Use. Intergovernmental Panel on Climate Change.Geneva, Switzerland.

IPCC. 2007. Climate change 2007: working group III: mitigation of climate change. IPCC fourth assessment report (AR4). Intergovernmental Panel on Climate Change. Geneva, Switzerland.

Lansing, S., Martin, J.F., Botero, R., da Silva, T.N., and da Silva, E.D. 2010. Wastewater transformations and fertilizer value when co-digesting differing ratios of swine manure and used cooking grease in low-cost digesters. *Biomass Bioenergy* 34: 1711-1720.

Massé, D.I., Massé, L., Xia, Y., and Gilbert, Y. 2010. Potential of low-temperature anaerobic digestion to address current environmental concerns on swine production. *Journal of Animal Science* 88:E112-E120.

McCarty, J.G. 2000. Methane combustion durable catalyst for cleaner air. *Nature* 403: 35-36.

Mendez-Gallegos, J.M., Rössel, D., Amante-Orozco, A., Gómez-González, A., and García-Herrera, J.E. 2010. El Nopal en la producción de biocombustibles. VIII Simposio-Taller Nacional y 1er Internacional "Producción y Aprovechamiento del Nopal", *Revista Salud Pública y Nutrición* 5: 70-84.

Milenio. 2011. *La energía limpia cuesta a ganaderos 115 mdp.* http://www.milenio.com/cdb/doc/impreso/8966880. (accessed 22 April 2013).

Montes, F., Meinen, R., Dell, C., Rotz, A., Hristov, A.N., Oh, J., Waghorn, G., Gerber, P.J., Henderson, B., Makkar, H.P.S., and Dijkstra, J. 2013. SPECIAL TOPICS-Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. *Journal of Animal Science* 91:5070-5094.

NMSU. New Mexico State University. 1999. *Insolation in Mexico. Azteca Solar*. The Mexico Renewable Energy Program 1992-2005. New Mexico State University, New Mexico, USA.

Rivas-Lucero, B.A., Zuñiga-Avila, G., Sáenz-Solis, J.I., Guerrero-Morales, S., Segovia-Lerma, A., and Morales-Morales, H.A. 2012. Perspectivas de obtención de energía renovable de la biomasa del estiércol del ganado lechero en la región centro-sur de Chihuahua. *Revista Mexicana de Agronegocios* 16(30): 872-885.

Sanders, D.J., Roberts, M.C., Ernst, S.C., and Thraen, C.S. 2010. Digesters and demographics: Identifying support for anaerobic digesters on dairy farms. *Journal of Dairy Science* 93:5503–5508.

Van Horn, H.H., Wilkie, A.C., Powers, W.J., and Nordstedt, R.A. 1994. Components of Dairy Manure Management Systems. *Journal of Dairy Science* 77:2008-2030.

Wang, Q., Thompson, E., Parsons, R., Rogers, G., and Dunn, D. 2011. Economic feasibility of converting cow manure to electricity: A case study of the CVPS Cow Power program in Vermont. *Journal of Dairy Science* 94:4937–4949.

Table 1. Composition of gases generated by bovine manure fermentation

Component	Concentration
Methane (CH_4)	55-65 %(vol)
Carbon dioxide (CO_2)	25-45 %(vol)
Water steam (H_2O)	2-7 %(vol)
Hydrogen sulfide (H_2S)	20-20000 ppm
Nitrogen (N_2)	< 2 %(vol)
Oxigen (O_2)	< 2 %(vol)
Hidrogen (H_2)	< 1 %(vol)

Abbasi et al. (2012)

Table 2. Manure generation and methane production from solid stored manure

Animal category	Manure generation, kg/d[¶]	Maximum methane production in manure, kg/d[€]
Lactating cows	68	0,087
Dry cows	38	0,067
Bulls	38	0,067
Heifers	22	0,051
Calves	8,5	0

[¶] ASAE (2005)

[€] Estimated with IPCC (2006) tier II, methodology

Table 3. Estimation of the initial investment and federal grants to acquire technology for generating electricity

Issue	Investment, US$	Maximum grants, US$
Lagoon digester	168259[A]	76923[B]
Digester installation	7615,4[C]	-
Electric generator, 60 kW-h	46153,8[A]	19230,7[D]
Generator installation	13846[D]	-
Solar panels, 10,34 kW	20774	10387[E]
Total	256648,2	106540,7
Total with grants	150107,5	-

[A] (Finanzas Carbono 2013)

[B] (FIRCO-SAGARPA 2013) up to 50% of the equipment cost or a maximum of US$ 76923

[C] (ASERCA 2007)

[D] (FIRCO-SAGARPA 2013) up to 50% of the equipment cost or a maximum of US$ 38461,5

[E] (ASERCA 2008) up to 50% of the equipment cost

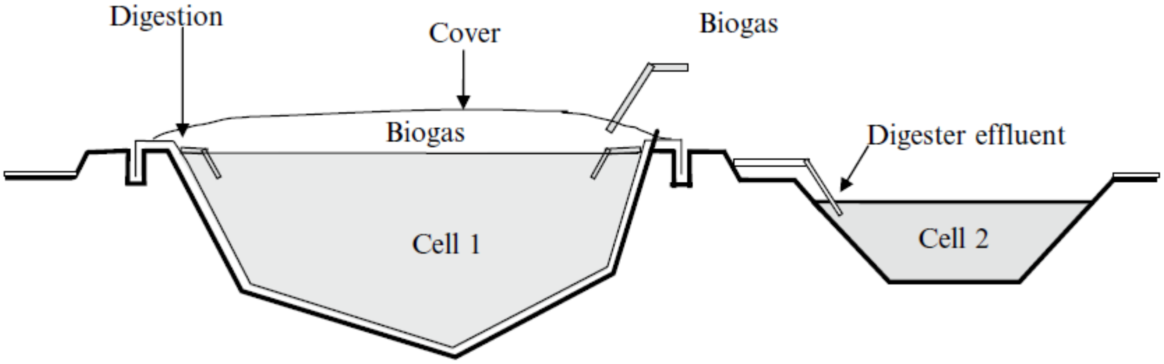

Figure 1. Graphic scheme of a covered lagoon digester (AgSTAR 2011).

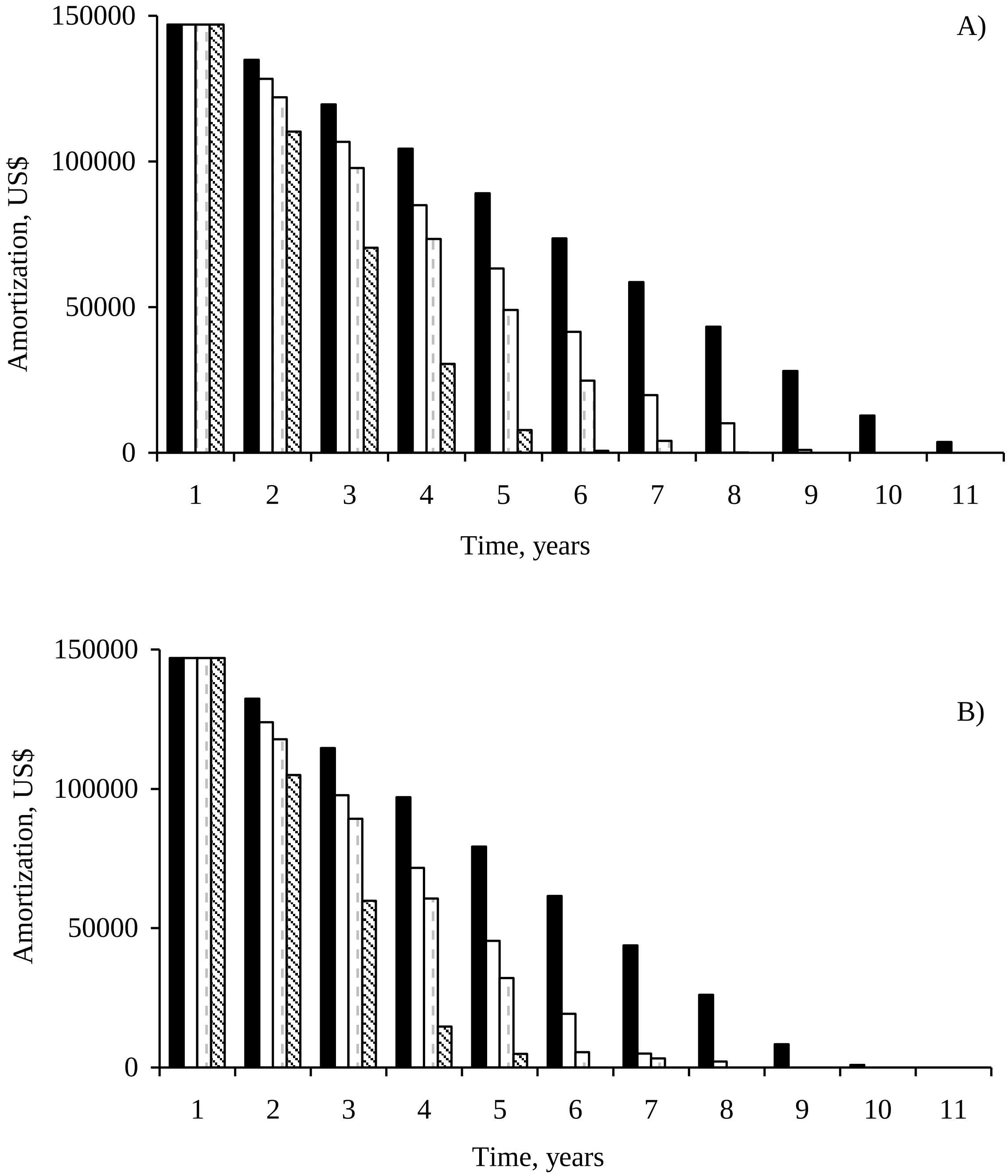

Figure 2. Investment amortization time for acquisition of a covered lagoon digester-generator and solar panels to generate electricity in dairies: 300-500 cows (■), 600-750 cows (□), 800-1000 cows (⬚), and 1150-1600 cows (▨). A) Simulated time of investment recovery with electricity generation only and, B) Simulated time of investment

recovery with electricity generation and sale of certificates of emission reduction, US $10/t$CO_2$eq, exchange rate, $13 Mexican pesos/US dollar (BANXICO 2013).

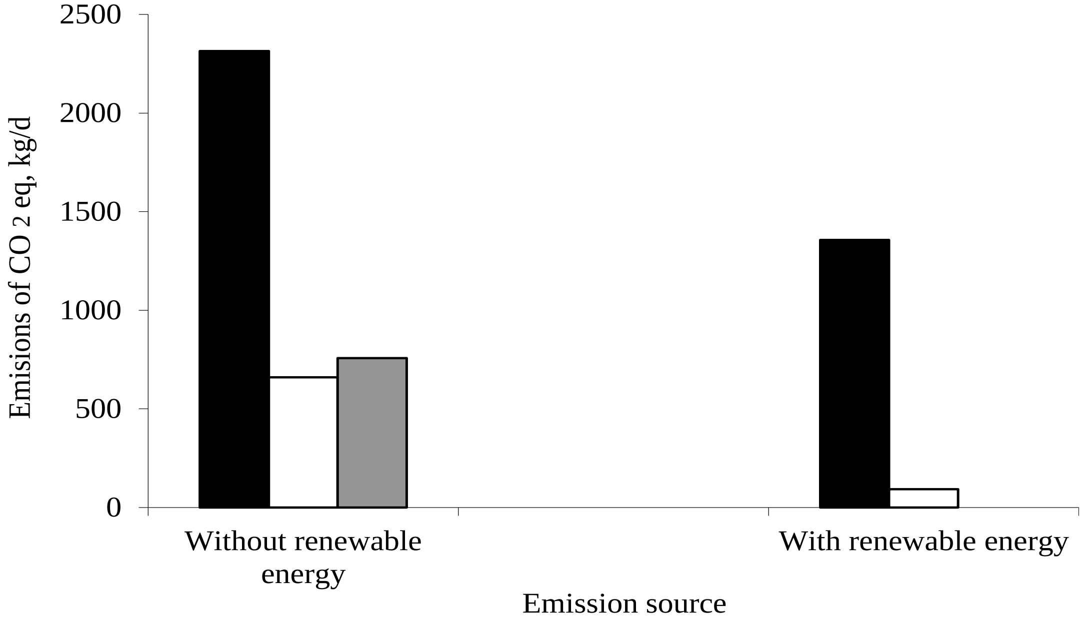

Figure 3. CO_2 equivalent emissions from consumption of electricity, with and without digester and solar panels, where main sources are electricity (■), methane (□), and nitrous oxide (▒).

Conclusiones generales

La producción de proteína de origen animal, como es el caso de la leche bovina, no está exenta de generar impactos negativos al ambiente. Los rumiantes por sus características digestivas generan gases de efecto invernadero (GEI). En países como el nuestro, donde el desarrollo de tecnología para la cuantificación de GEI es escaso, se puede recurrir al uso de modelos matemáticos específicos que nos den un aproximado de la energía y nutrientes (N, P y K) que no son aprovechados por las vacas y que son excretados hacia el ambiente (suelo, agua y atmósfera).

En los últimos 40 años, la mejora en la eficiencia de producción de leche bovina en México ha permitido disminuir la huella de carbono por litro de leche producido. Esta disminución podría llegar a ser más importante en el futuro, tan pronto y los distintos sistemas de producción incrementen la eficiencia de producción por vaca y se modifiquen las prácticas de manejo de estiércol para el aprovechamiento de energía.

Aun cuando el tamaño, el consumo de materia seca y por ende la excreción de residuos orgánicos por vacas en producción se ha incrementado en los últimos años, la producción de leche por vaca lo ha hecho de la misma manera y esto se ha logrado mejorando la calidad de forrajes, los alimentos, la genética de las vacas y al confort animal. Aun cuando los sistemas de producción de leche con mayor grado de intensidad hacen un mayor uso de fuentes de energía externa como combustibles fósiles, electricidad y fertilizantes, éstos resultan ser menos contaminantes por unidad de producto.

La utilización de energía alterna como paneles solares y digestores anaerobios, contribuyen de manera importante en la mitigación de GEI generados en las granjas lecheras.

Implicaciones

El estudio integral de la comparación de sistemas con distintos grados de intensidad sobre las emisiones de gases de efecto invernadero y posibles estrategias de mitigación de los mismos por establos lecheros estabulados, podría generar un modelo más completo de predicción con enfoque a un análisis de ciclo de vida. Además, con infraestructura y equipos se podrán validar los datos para desarrollar el modelo nivel III (mecánico-dinámico) para nuestro país, tal como lo propone el IPCC.

ANEXO

Programa Multidisciplinario en Posgrado en Ciencias Ambientales, Universidad Autónoma de San Luis Potosí (UASLP)

Cuestionario

Presentación: A los productores de ganado lechero, se les hace una atenta invitación a participar en el estudio titulado impacto ambiental de la ganadería lechera. La finalidad es llevar un control de las emisiones y mitigar las mismas a través de mejores prácticas de manejo, los resultados se tratarán con confidencialidad y se entregarán a los participantes.

1.- ¿Número de animales con que cuenta?

Vacas lactando _______ Vacas secas ______ Novillas _______ Toros _____

2.- ¿Número de animales en producción por categoría?

Super altas________ Altas ________ Medias ________ Bajas_______

Peso promedio

Super altas________ Altas ________ Medias ________ Bajas________ Consumo de materia seca día^{-1}

Super altas_____ Altas ______ Medias ______ Bajas_____ Secas_____

Composición de las raciones (Ingredientes)

Super altas	Altas	Medias	Bajas	Secas
_____________	___________	____________	___________	__________
_____________	___________	____________	___________	__________
_____________	___________	____________	___________	__________
_____________	___________	____________	___________	__________

______________	____________	_____________	____________	___________
______________	____________	_____________	____________	___________
______________	____________	_____________	____________	___________
______________	____________	_____________	____________	___________
______________	____________	_____________	____________	___________

3.- ¿Cantidad de leche producida, animal/día?

4.- ¿Cuál es el tamaño de las instalaciones?

Con cuantos corrales cuenta? ________

Cuántos animales existen por corral? _________

5.- ¿Producen sus propios alimentos? si_____ no______

En caso de ser positiva la respuesta, ¿Podría mencionarlos?

Cultivo	Área de siembra	Rendimiento, Hectárea
______________________	_______________________	_____________________
______________________	_______________________	_____________________
______________________	_______________________	_____________________
______________________	_______________________	_____________________
______________________	_______________________	_____________________
______________________	_______________________	_____________________
______________________	_______________________	_____________________

6.- ¿Cantidad de agua que se gasta al día en, Bebederos _________,

Limpieza de corrales _________

Limpieza de sala ordeño _________

Irrigación __________

7.- ¿Cantidad de energía eléctrica que se consume, bimestre?

Sala de ordeño _____________

Irrigación (pozos) ___________

Iluminacion oficinas-casa ______________

8.- ¿Cuentan con tractores, camiones y/o camionetas? Si_____ No______

¿Número de camionetas? _______ Consumo, gasolina/semana _________

¿Numero de Tractores?________ Consumo, Diesel/semana ________

9.- ¿Cantidad de estiércol que se produce al día?

10.- ¿Qué se le hace al estiércol?

Almacena al aire libre____ Vende _____ Separa Líquidos_____ Digestor Anaerobio____

11.- ¿Si se almacena, cuánto tiempo permanece en almacén?