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Research paper

Feeding and fertilization practices and greenhouse gas emissions in specialized dairy farms of Dos Pinos in Costa Rica

Prácticas de alimentación animal y de fertilización, y emisión de gases de efecto invernadero en granjas lecheras de Dos Pinos, Costa Rica

MICHEL A. WATTIAUX[1], JUAN PABLO IÑAMAGUA-UYAGUARI[2,3], LEONARDO GUERRA[2,4], FRANCISCO CASASOLA[2] AND ANDREAS JENET[2]

[1]*Dairy Science Department, University of Wisconsin, Madison, WI, USA.* http://dysci.wisc.edu
[2]*Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Turrialba, Costa Rica*. www.catie.ac.cr
[3]*Facultad de Ciencias Agropecuarias, Universidad de Cuenca, Cuenca, Ecuador*. www.ucuenca.edu.ec
[4]*Centro Transdisciplinario de Estudios Ambientales y Desarrollo Humano Sostenible, Universidad Austral de Chile, Valdivia, Chile.* www.ceam-uach.cl

Abstract

Emissions of methane (CH_4) and nitrous oxide (N_2O) based on the feeding systems of 104 dairy farms in Costa Rica were estimated using IPCC procedures. This study indicated that farmers' decisions, which determine the feeding strategies for lactating cows, have a substantial impact on CH_4 emissions per kg of milk. Lower CH_4 emissions per kg milk were estimated on farms with high-producing cows consuming rations with lower neutral detergent fiber concentrations and higher amounts of concentrates. Hours spent in pasture did not influence estimated grass intake or CH_4 emissions. However, higher feed efficiency appeared to be a key factor in reducing CH_4 emissions per kg of milk. The study also showed that higher N_2O emissions were associated with higher amounts of commercial nitrogen fertilizer application; however, the main source of N_2O emissions was from the manure deposited during the grazing period. Future approaches to reduce farm gate emissions of CH_4 per kg of milk in specialized dairy farms could include incorporating dietary fats in rations, feeding adequate amounts of concentrates and feeding forage at a more digestible stage. These findings are strongly influenced by the assumptions made in calculating CH_4 and N_2O emissions but do highlight the critical areas which affect greenhouse gas emissions.

Keywords: Feed efficiency, fertilization, forage, manure, methane, nitrous oxide.

Resumen

Se estimaron las emisiones de metano (CH_4) y óxido nitroso (N_2O) en 104 granjas lecheras en Costa Rica, utilizando los procedimientos del IPCC. El estudio indica que las decisiones de los productores respecto a las estrategias de alimentación de sus vacas en ordeño tienen un impacto sustancial en las emisiones de CH_4 por kg de leche. Se estimaron emisiones de CH_4 bajas por kg de leche en aquellas granjas donde las vacas de alta producción consumían raciones con concentraciones menores de fibra detergente neutro y cantidades mayores de concentrados. Las horas dedicadas al pastoreo no influyeron en las estimaciones del consumo de pasto ni en las emisiones de CH_4. Sin embargo, una mayor eficiencia alimenticia parecía ser un factor clave en la reducción de las emisiones de CH_4 por kg de leche. El estudio también mostró que emisiones de N_2O más altas estaban asociadas con la aplicación de mayores cantidades de fertilizantes comerciales de nitrógeno. Sin embargo, la principal fuente de emisiones de N_2O fueron las excretas de las vacas durante el pastoreo. Futuras estrategias para reducir, a nivel de granja, las emisiones de CH_4 por kg de leche en las

Correspondence: A. Jenet, CATIE, 30501 Turrialba, Costa Rica.
Email: a.jenet@alumni.ethz.ch

explotaciones lecheras especializadas, podrían incluir la incorporación de grasas alimenticias en las raciones, alimentación con cantidades adecuadas de concentrados y alimentación con forrajes más digeribles. Aunque estos resultados estén fuertemente influenciados por los supuestos que se emplean en los cálculos de las emisiones de CH_4 y N_2O, sí realzan las áreas críticas que determinan las emisiones de gases de efecto invernadero a nivel de granja lechera.

Palabras clave: Eficiencia alimenticia, excreta, fertilización, forraje, metano, óxido nitroso.

Introduction

The specialized dairy industry of Costa Rica can play an important role in helping the country reduce its national inventory of the 3 main gases that trap heat in the atmosphere: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). For ease of comparison and interpretation, greenhouse gas emissions are typically expressed as carbon dioxide equivalent (CO_2-eq) to account for the differing amounts of each gas released and its effectiveness in trapping heat. Chacón et al. (2009) calculated that agriculture contributed 37% of all greenhouse gas emissions of Costa Rica in 2005, with the livestock sector responsible for the majority of these emissions.

Dairy farmers' decisions on how to feed their cows have a substantial impact on emissions of CH_4 produced during fermentation of feed, primarily in the rumen and secondly in the caecum of the large intestine. These emissions are referred to as enteric emissions, or emissions from the digestive system. In addition, farmers' decisions on how to fertilize pastures have a substantial impact on the emissions of N_2O from the soil. Furthermore, decisions on how to manage manure (feces + urine) collected from the barn may also influence substantially CH_4 and N_2O emissions.

The objective of this article is to share the results of a study we conducted to estimate the impact of farmers' management decisions on the emissions of CH_4 from lactating cows and N_2O from pastures on specialized dairy farms associated with Costa Rica's largest dairy cooperative, Dos Pinos. The study focused on the important sources of emissions within the farm, often referred to as "farm gate" emissions, but did not provide a full account of the carbon footprint of milk production, which would require estimating the emissions associated with the production of all inputs used on farms and the emissions associated with transport, milk processing, packaging and storing until consumption. Specifically, we studied the following relationships:

- Enteric CH_4 emissions associated with the farmers' decisions on how to feed lactating cows;
- Nitrous oxide emissions from soils associated with the farmers' decisions about:
  - Nitrogen (N) fertilizing of grazed pastures with commercial fertilizers;
  - N fertilizing of cut-and-carry pastures with commercial fertilizers; and
  - Organic N fertilizing of grazed pastures through manure (feces + urine) deposited by the cows during the grazing period.

Materials and Methods

Source of the data

Most of the data for this study were obtained in a survey conducted in December 2013 and January 2014 among producers of the Cooperativa Dos Pinos (see Figure 1 for locations). Since the amount of feed consumed and the chemical composition of the diet are critical in estimating CH_4 emissions, farmers were asked to list all feeds and amounts offered to their lactating cows. We relied also on the equations of the National Research Council (NRC 2001) to determine how much feed cows consumed per day, and subtracted the amount of feed offered in the dairy from total feed consumption to determine intake of grass from pasture. Similarly, as N applied per hectare and per year is critical in estimating N_2O emissions, farmers were asked to list all fertilizers and amounts applied during each pasture rotation cycle or each cut-and-carry cycle, as well as the number of hours that cows spent in the pasture each day (to calculate the proportion of manure N deposited in the pasture).

Pasture distribution frequency

Data from the 104 farms allowed the identification and evaluation of the most dominant pasture and forage species. Georeferenced farms, including their grass species and forage inventory, were categorized using the ecological life zones of Costa Rica (Bolaños et al. 1999) established after the Holdridge life zones (Holdridge 1967) and related with climate data from WorldClim database (Hijmans et al. 2005) in order to calculate

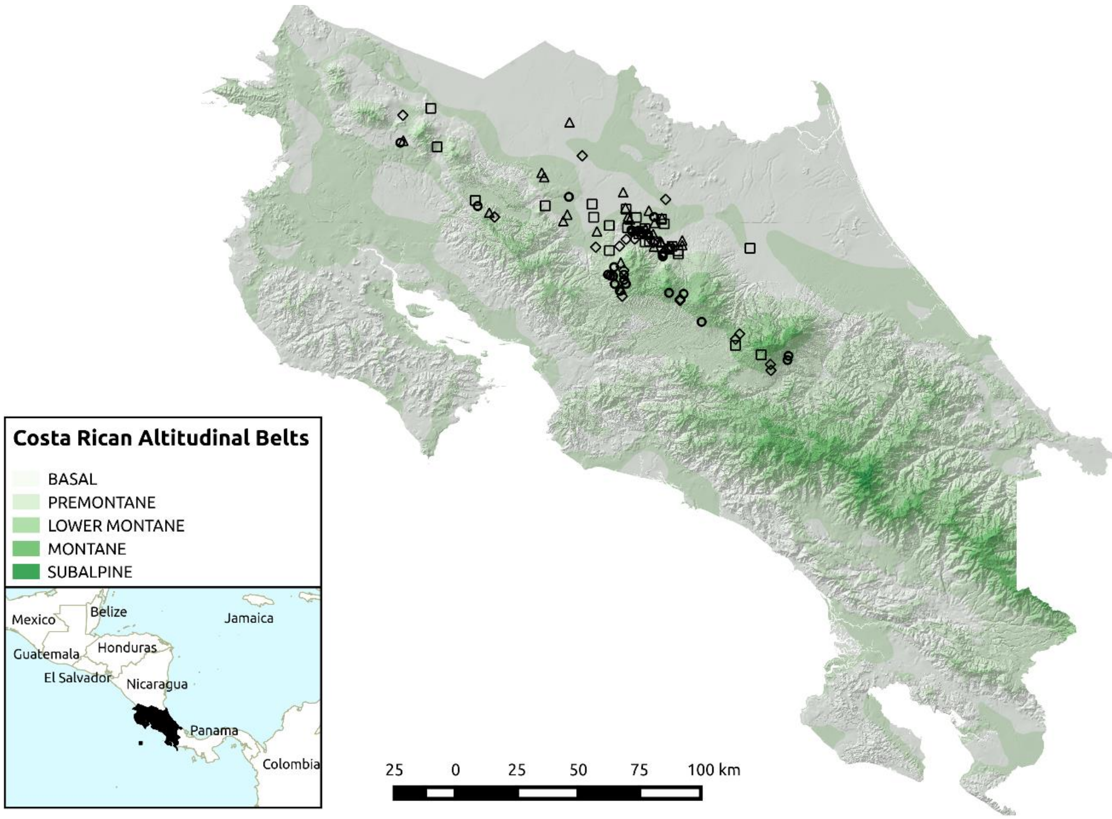

Figure 1. Distribution of locations of the 104 specialized Cooperativa Dos Pinos dairy farms in Costa Rica included in the study labeled in quartiles of partial carbon footprint (kg CO_2-eq per kg of fat-and-protein corrected milk) (Triangle = high emitters: 0.67 to 1.17; diamond = medium-high emitters: 0.59 to 0.67; squares = medium-low emitters: 0.51 to 0.59; circle = low emitters: 0.38 to 0.51); map colors represent 5 elevation zones based on Holdridge's ecological life zones (Bolaños et al. 1999).

average elevation, rainfall and temperature for each grass species. Grass species frequency distribution within ecological life zones was summarized using the grass species reported in each farm and information obtained from the "Digital Atlas of Costa Rica" (Ortiz-Malavassi 2009).

Estimating methane and nitrous oxide emissions

Calculations of CH_4 and N_2O emissions are complex and include a large degree of uncertainty. However, we used equations recommended by the international scientific organization responsible for studying greenhouse gas emissions and climate change, known by its English acronym as IPCC (Intergovernmental Panel on Climate Change; IPCC 2016). Estimated daily CH_4 emissions were converted to annual emissions based on the number of lactating cows on the farm, which in turn were converted to amounts of CO_2-eq to account for the fact that CH_4 is 21 times more potent than CO_2 (the main greenhouse gas) at trapping heat in the atmosphere and changing the climate (Dong et al. 2006). Finally, we calculated the emissions of CO_2-eq from CH_4 per kg of milk produced by the herd after standardizing milk production to a common fat and protein content, referred to as fat-and-protein-corrected milk (FPC-milk) as recommended by the International Dairy Federation (IDF 2010).

The N_2O emissions per hectare from commercial fertilizer were estimated as 1% of the N applied on grazed pasture and cut-and-carry areas (de Klein et al. 2006), and subsequently converted to annual N_2O emissions based on respective areas within the farm. To estimate the N_2O emissions from manure, i.e. the N voided by the cows in feces and urine during the daily grazing period, we used a N balance approach, assuming that, on average, the N consumed daily that is not excreted in the milk on that day is voided in feces and urine (Dong et al. 2006; Olmos Colmenero and Broderick 2006). The N_2O emitted from pastures for lactating cows was then calculated as the sum of the N_2O emitted from commercial fertilizers and that arising from manure. This amount was then converted to CO_2-eq to account for the fact that N_2O is 310 times more potent than CO_2 at trapping heat in the atmosphere and changing the climate (de Klein et al. 2006). Finally, we calculated the emissions of CO_2-eq from N_2O per kg of FPC-milk produced by the herd.

Partial carbon footprint of milk

The emissions from the farm were calculated as the sum of the annual emissions of CH_4 from lactating cows and the annual emissions of N_2O from the land of the farm (from the 3 sources discussed above). Then, the partial carbon footprint (CO_2-eq/kg FPC-milk) was calculated as total farm emissions divided by the FPC-milk produced annually by the lactating cows.

Determining farms with high and low emissions

Our goal was to determine farm characteristics that influenced estimated emissions of CH_4, N_2O and the partial carbon footprint. Thus for each of these emissions, we listed the 104 farms in the study from the lowest to the highest emitter and then divided the farms into 4 groups of 26 farms each, including the lowest emitters (first quartile: bottom 25% of the farms), the medium-low emitters (second quartile: 26^{th} to 50^{th} percentiles of the farms), the medium-high emitters (third quartile: 51^{st} to 75^{th} percentiles of the farms) and the highest emitters (fourth quartile: top 25% of the farms). Then, for each group, we calculated and tabulated the average of selected variables, describing farm characteristics and management decisions of the producers.

Results

Pasture distribution frequency

A wide variety of pasture and forage species was found on the farms (Tables 1 and 2). Even though the distribution frequency of species varied among the different climatic zones depending on elevation and rainfall, several pasture species were found in a number of climatic zones (Table 1). Most abundant species in the basal climatic zone were tanner [*Brachiaria* (now *Urochloa*) *arrecta*], brizantha [*Brachiaria* (now *Urochloa*) *brizantha*] and ratana (*Ischaemum ciliare*). In the premontane climatic zone the most dominant species were found to be estrella (African star grass, *Cynodon nlemfuensis*) and brizantha, while kikuyu (*Pennisetum clandestinum*) and estrella were predominant in the lower montane zone.

The use of cut-and-carry forage species was widespread among the surveyed dairy farms (Table 2). Most frequently used species were king grass (*Pennisetum* hybrid), kikuyu (*P. clandestinum*) and cameroon (*P. purpureum*). Most forage species were used in more than one climatic zone except kikuyu and rye grass (*Lolium perenne*), which were grown in the lower montane climatic zone only.

Table 1. Most important grazed pasture species with average elevation (Elv) of their respective farms, average rainfall (R), average temperature (T) and use frequency ranking in climatic zones.

Species	Elv	R	T	Use frequency ranking in climatic zones[1] (n)		
	(masl)	(mm/yr)	(ºC)	1st	2nd	3rd
Pennisetum clandestinum (n=15)	1,847	2,800	16	LM (15)		
Brachiaria arrecta x mutica (n=6)	600	3,631	23	B (3)	P (2)	M (1)
Ischaemum ciliare (n=19)	268	3,644	25	B (11)	P (8)	
Panicum maximum (n=3)	300	3,903	25	P (2)	B (1)	
Brachiaria brizantha CIAT-26110 (cv. Toledo) (n=3)	400	4,178	25	B (2)	P (1)	
Brachiaria decumbens (n=6)	500	3,552	24	B (4)	P (2)	
Brachiaria arrecta (n=23)	535	4,311	24	B (14)	P (9)	
Brachiaria brizantha CIAT-26124 (n=23)	287	3,627	25	B (12)	P (11)	
Cynodon nlemfuensis (n=41)	690	3,303	23	P (22)	B (10)	LM (9)
Brachiaria hybrid CIAT line FM 9201/1873 (cv. Mulato) (n=3)	133	3,618	26	P (2)	B (1)	
Brachiaria brizantha (n=8)	450	3,689	24	P (5)	B (3)	
Lolium perenne (n=1)	1,700	2,924	17	LM (1)		

[1]Climatic zones categorized according to Holdridge (1967) as LM = lower montane; B = basal; P = premontane; M = montane. 1st = most frequent; 2nd = second most frequent; 3rd = third most frequent. Numbers in parentheses indicate the number of farms (n) in which species were observed.

Table 2. Most important cut-and-carry forage species with average elevation (Elv) of their respective farms, average rainfall (R), average temperature (T) and use frequency ranking in climatic zones.

Species	Elv (masl)	R (mm/yr)	T (ºC)	Use frequency ranking in climatic zones[1] (n) 1st	2nd	3rd
Pennisetum clandestinum (kikuyu) (n=9)	1,755	2,808	17	LM (9)		
Pennisetum sp. (maralfalfa) (n=11)	636	3,854	23	B (5)	P (4)	LM (2)
Pennisetum sp. (king grass) (n=12)	608	4,196	24	B (6)	P (6)	
Digitaria swazilandensis (suazi) (n=4)	250	3,676	25	B (2)	P (2)	
Panicum maximum cv. Mombaza (n=6)	467	4,275	24	B (4)	P (2)	
Pennisetum purpureum (cameroon) (n=7)	900	3,393	22	B (3)	LM (3)	P (1)
Lolium perenne (rye grass) (n=4)	1,775	2,666	17	LM (4)		

[1]Climatic zones categorized according to Holdridge (1967) as LM = lower montane; B = basal; P = premontane; M = montane. 1st = most frequent; 2nd = second most frequent; 3rd = third most frequent. Numbers in parentheses indicate the number of farms (n) in which species were observed.

Methane emissions

How much methane is produced? Estimated CH_4 emissions averaged 266 g/cow/d, but varied considerably (standard deviation = 55 g/cow/d). To give ourselves confidence in the prediction of CH_4 emissions, we compared our results with the predictions obtained from the equation proposed by Moraes et al. (2014), which was based on ration and animal characteristics, and the equation proposed by Ramin and Huhtanen (2013), which was based solely on feed consumption (dry matter intake). These equations yielded averages of 231 and 326 g/cow/d, respectively. Although the difference between these estimates was substantial, our estimation of CH_4 emissions was within the range of these literature values. Our estimate of annual CH_4 emissions was 97 kg/cow (266 g/cow/d x 365 d), which was higher than the IPCC (tier 1) value of 63 kg/cow (Dong et al. 2006). The IPCC value, however, assumed a considerably lower level of milk production (800 kg/cow/yr) than those produced on the farms in this study (range 4,000–7,000 kg/cow/yr). Estimated CH_4 emissions expressed as CO_2-eq/kg FPC-milk averaged 419 g, but ranged from 316 to 636 g for different farms. As indicated in Table 3, lactating cows in farms of the first, second, third and fourth quartiles had average emissions of 342, 386, 428 and 519 g CO_2-eq/kg FPC-milk, respectively.

What factors are associated with high and low methane emissions? Cow characteristics, concentrate feeding and time in pasture had a marked influence on our estimated CH_4 emissions per kg of FPC-milk (Table 3). Our interpretation of these effects is as follows:

1. Farms that emitted the lowest amount of CH_4 per kg of FPC-milk were those where CH_4 emissions per cow were highest. Methane production per cow was a reflection of the amount and the composition of the feed consumed by the cow, regardless of milk production. Thus, in general, cows that consumed more feed produced more CH_4 but also produced (proportionally) more milk. Results indicated that less CH_4 was produced per kg of FPC-milk when cows consumed more feed and produced more CH_4 per day but also produced more milk.
2. Estimated emissions of CH_4 per kg of FPC-milk were lowest in herds that had the highest feed efficiency. Feed efficiency is calculated as milk production (kg/d) per unit of dry matter intake (feed consumption, kg/d), and is a partial reflection of the farmer's ability to feed and manage cows to produce the highest possible amount of milk for each kg of feed consumed.
3. Estimated emissions of CH_4 per kg of FPC-milk were lowest when cows were fed more concentrates. As concentrate feeding (DM basis) increased from 3.3 to 6.1 kg/cow/d, estimated CH_4 emissions decreased from 0.52 to 0.34 kg CO_2-eq/kg FPC-milk. These results are consistent with those reported by Aguerre et al. (2011), indicating that increasing the proportion of concentrates and reducing the proportion of forage in the diet decreases CH_4 emissions per kg of milk produced.

Does diet composition make a difference? To investigate further the effects of diet composition on estimated CH_4 emissions, we grouped the 104 farms into 4 quartiles based on amounts of concentrate offered to the cows. Average amount of concentrate (DM basis) offered ranged from 2.1 kg/cow/d (low concentrate users) to 7.2 kg/cow/d (high concentrate users). Results summarized in Table 4 indicate that producers who fed more concentrates to their cows did not offer greatly different amounts of by-product feeds or forage dry matter in the

Table 3. Estimated enteric methane (CH_4) emissions and feeding practices for specialized dairy farms (n=104) ranked in quartiles according to estimated level of enteric CH_4 emissions[1].

Parameter	CH_4 emission quartile[1] (g CO_2-eq/kg FPC-milk)			
	4th	3rd	2nd	1st
	519	428	386	342
CH_4 (kg/cow/d)	0.23	0.25	0.27	0.32
CH_4 (kg/cow/yr)	83	92	99	115
Cow characteristics:				
Cow body weight (kg)	408	410	426	438
FPC-milk (kg/cow/d)	9.7	13.0	16.0	20.0
DMI[2] (kg/cow/d)	13.8	15.2	16.6	18.3
Feed efficiency (kg FPC-milk/kg DMI)	0.70	0.85	0.96	1.08
Feeding and management strategies:				
Concentrate (kg DM/cow/d)	3.3	4.2	5.5	6.1
Time in pasture (h/cow/d)	18	17	17	16

[1]1st, 2nd, 3rd and 4th quartile = farms with low, medium-low, medium-high and high enteric CH_4 emissions expressed as CO_2-eq per kg of fat-and-protein-corrected milk (FPC-milk), respectively.
[2]DMI = Dry matter intake estimate based on NRC (2001) equation.

form of purchased hay or silage or grass from cut-and-carry pastures. Interestingly grass dry matter intake, which declined slightly when more concentrate was offered to the cows, was not affected by time in the pasture, which was increased by farmers who offered more concentrates to their cows. Overall, as concentrate feeding increased, total dry matter intake also increased as did milk production and feed efficiency (Table 4). Dietary neutral detergent fiber concentrations observed in this study were high for lactating cow diets (NRC 2001) and were likely to limit the total amount of feed that cows could consume and process per day (Mertens 1997). Feeding additional concentrates with low neutral detergent fiber would result in higher total feed consumption, higher milk production and thus higher feed conversion efficiency (Table 4). As a result of these compounded effects, increasing the amount of concentrates fed to the cows was estimated to increase daily CH_4 emissions by the cows, but reduced the CH_4 emissions expressed as kg CO_2-eq/kg of FPC-milk produced on the farm (Table 4). The low levels of crude fat reported in Table 4 suggested that inclusion of supplemental dietary fats may be an avenue to reduce CH_4 emissions from dairy cows in Costa Rica. Although fats are normally minor constituents of dairy cow rations, a slight increase in fat concentration may reduce CH_4 emissions/kg FPC-milk (Martin et al. 2010).

Does time in pasture make a difference? The answer is "probably not". As shown above in Table 3, the average time spent in pasture daily declined only slightly from the highest CH_4-emitting herds to the lowest CH_4-emitting herds. Similarly, the estimated amount of grass dry matter consumed from the pasture was almost identical among the 4 groups of farms. This result suggested that consumption of grass was not limited by time in pasture.

Nitrous oxide emissions

How much nitrous oxide is produced? Most common N fertilizers for cut-and-carry forage production were: a chemical NPK fertilizer (10-30-10) applied on 13% of the farms; urea applied at least once per year on 11% of the farms; and ammonium nitrate on 11% of the farms (Nutran, 33.5% N). Common N fertilizers applied on pastures were: ammonium nitrate (Nutran, 33.5% N) used on 37% of the farms; urea on 32% of the farms; magnesium ammonium nitrate (21% N, 11% Ca, 7.5% Mg) applied on 24% of the farms; and a chemical NPK fertilizer 10-30-10 applied on 21% of farms.

Estimated N_2O emissions expressed as kg N_2O/ha/yr are presented in Table 5. Estimated emissions from the application of commercial N fertilizer averaged 2.76 kg N_2O/ha/yr but the standard deviation was high (2.57 kg N_2O/ha/yr) indicating high variation among farms. Nevertheless, the average value was comparable with emission values of 1.23 kg N_2O/ha/yr without fertilizer application and 2.44 kg N_2O/ha/yr after applying 200 kg N/ha/yr to a kikuyu pasture reported by Montenegro and Herrera (2013). When expressed as kg CO_2-eq/kg FPC-milk, N_2O emissions averaged 198 g CO_2-eq/kg milk, but ranged from 56 to 536 g CO_2-eq/kg milk. As indicated in Table 5, average N_2O emissions on farms in the first, second, third and fourth quartiles were 108, 157, 200 and 328 g CO_2-eq/kg FPC-milk, respectively.

Table 4. Estimated enteric methane (CH_4) emissions and feeding practices for specialized dairy farms (n=104) ranked in quartiles according to the amounts of concentrates consumed by the lactating cows[1].

Parameter	Concentrate consumption quartile[1] (kg DM/cow/d)			
	4th	3rd	2nd	1st
	7.2	5.2	4.2	2.1
Enteric CH_4 emission				
g CH_4/cow/d	304	265	243	251
g CO_2-eq/kg PFC-milk	371	394	429	481
Dietary ingredients				
Concentrates (kg DM/cow/d)	7.2	5.2	4.2	2.1
By-products (kg DM/cow/d)	1.7	1.8	1.0	1.3
Forage[2] (kg DM/cow/d)	1.1	1.2	2.1	1.2
Grazed pasture[3] (kg DM/cow/d)	7.7	7.7	7.2	9.5
DMI (kg/cow/d)	17.8	15.9	14.6	14.1
Time on pasture (h/cow/d)	18	18	16	17
Estimated dietary composition				
Crude protein (% DM)	14	13	12	12
Neutral detergent fiber (% DM)	39	45	49	54
Crude fat[4] (% DM)	2.9	2.7	2.5	2.4
Milk production and efficiency				
FPC-milk[5] (kg/cow/d)	17.7	14.3	12.2	11.7
Feed efficiency (kg FPC-milk/kg DMI)	0.99	0.90	0.84	0.81

[1]1st, 2nd, 3rd and 4th quartile = farms with low, medium-low, medium-high and high concentrate consumption by lactating cows, expressed as kg per cow per day, respectively.
[2]Forage dry matter offered in the barn included purchased hay, purchased silage in plastic bales and grass from cut-and-carry pastures.
[3]Grazed pasture intake calculated by difference between dry matter intake (DMI) estimated from NRC (2001) equation and the sum of all other dietary ingredients.
[4]Crude fat = total fat measured by ether extract procedure.
[5]FPC-milk = fat-and-protein-corrected milk production (IDF 2010).

Table 5. Estimated nitrous oxide (N_2O) emissions and fertilizer practices for specialized dairy farms (n=104) ranked in quartiles according to estimated level of N_2O emissions[1].

Parameter	N_2O emission quartile[1](g CO_2-eq/kg FPC-milk)			
	4th	3rd	2nd	1st
	328	200	157	108
N_2O emissions (kg/ha/yr) from:				
Commercial fertilizer on grazed pasture	4.2	3.6	2.2	1.1
Commercial fertilizer on cut-and-carry grass	2.2	1.5	1.1	0.7
Manure (feces + urine) on grazed pasture	6.3	7.8	8.3	6.0
N fertilizer (kg N/ha/yr):				
Commercial fertilizer on grazed pasture	267	229	138	68
Commercial fertilizer on cut-and-carry grass	141	96	70	42
Manure (feces + urine) on grazed pasture	201	249	265	192
Time on pasture (h/d)	18	17	17	15
N balance of the cow (g/cow/d):				
Nitrogen intake	303	337	343	315
Milk nitrogen	57	77	80	83
Manure nitrogen	245	260	263	232
N use efficiency[2] (%)	19	23	23	26

[1]1st, 2nd, 3rd and 4th quartile = farms with low, medium-low, medium-high and high N_2O emissions expressed as CO_2-eq/kg fat-and-protein-corrected milk produced (FPC-milk), respectively.
[2]Nitrogen use efficiency (%) = 100 x milk N (g/d) / N intake (g/d).

What factors are associated with high and low nitrous oxide emissions? Table 5 shows estimated N_2O emissions in relation to N fertilizer application from commercial fertilizers and manure N deposited by the cows during grazing. Main factors influencing N_2O emissions per kg FPC-milk and interpretation of these effects are as follows:

1. On all farms, the main source of N_2O emissions was manure deposited by the cows during grazing rather than commercial fertilizers. Among quartiles, estimated N_2O emissions from manure ranged from 6.0 to 8.3 kg N_2O/ha/yr, whereas estimated N_2O emissions from commercial fertilizer applied to pasture and to cut-and-carry grass ranged from 1.1 to 4.2 and from 0.7 to 2.2 kg N_2O/ha/yr, respectively. The amounts of commercial fertilizer N applied to pasture and to cut-and-carry grass annually were 176 and 87 kg N/ha/yr, but the average amount of manure N deposited by lactating cows during grazing was estimated as 227 kg N/ha/yr. As suggested by the data presented in Table 5, on at least 75% of the farms (those in the 1st, 2nd and 3rd quartiles), the amount of N deposited in feces and urine by cows during grazing was higher than the amount of N applied as commercial fertilizer.
2. Extremes in estimated N_2O emissions per kg FPC-milk were associated with extremes in amount of commercial N application. In this study 13 farmers (13% of the farmers) applied no commercial fertilizer to pasture grazed by lactating cows, while 15 farmers (14% of the farmers) applied more than 300 kg N/ha/yr. These extremes in N application explained in large part the variation in N_2O emissions observed in this study.
3. Estimated N_2O emissions per kg FPC-milk from manure deposited by the cows during grazing depended on a combination of factors, but remained fairly consistent among all farms in the study. The amount of N deposited on the pasture by cows depended upon the length of time spent on pasture per day and the amount of manure excreted per day. The latter increased with level of dry matter intake (and milk production) and with N concentration in the manure, which in turn depended partly on crude protein concentration in the diet. Crude protein concentration was low in the pasture for lactating cows (NRC 2001), but increased with the amount of concentrate fed to the cows (Table 4).
4. Estimated N_2O emissions per kg FPC-milk were lowest on farms in which N use efficiency for milk production was highest. Nitrogen use efficiency, or the percentage of the N consumed by the cows which was converted to milk N, was low, averaging 19%, among the high N_2O-emitting farms, but was substantially better, averaging 26%, among the low-emitting farms.

Does the amount of commercial fertilizer applied make a difference? To investigate further the effects of the application of commercial fertilizer on N_2O emissions, we grouped the 104 farms of this study into 4 quartiles based on amount of N fertilizer applied per hectare of pasture. Average N application ranged from a low 20 kg N/ha among the low N fertilizer users to a high 383 kg N/ha among the high N fertilizer users. Data in Table 6 indicated that estimated dry matter intake, milk production and feed efficiency were not affected by level of commercial N application to grazing pasture. As a result, increases in N applied as commercial fertilizer resulted in increases in N_2O emissions per hectare of pasture and N_2O emissions expressed as g CO_2-eq/kg PFC-milk. Technical support personnel in Dos Pinos indicated that current recommendations for commercial N application are approximately 250 kg N/ha/yr. These recommendations are made regardless of the amount of manure N deposited by cows during grazing, which, as indicated in Table 5, ranged from 192 to 265 kg N/ha/yr. Our data do not support recommendations for high commercial N application on grazing pasture under the assumption that more fertilizer means more grass (i.e. more feed) for the cows and thus more milk per cow. The feeding practices and estimated dietary composition findings described above support this conclusion because grass intake was relatively constant on all farms regardless of feeding strategies. This conclusion is consistent with recent findings at the University of Costa Rica, indicating that cows consume only 30–45% of the total amount of grass biomass available in pasture (Villalobos and Sánchez 2010; Villalobos et al. 2013).

Table 6. Estimated nitrous oxide (N_2O) emissions and cow performance for specialized dairy farms (n=104) ranked in quartiles according to level of commercial N fertilizer application[1].

Parameter	N fertilizer application quartile[1] (kg N/ha/yr)			
	4th	3rd	2nd	1st
	383	197	102	20
N_2O release (kg/ha/yr)	6.02	3.10	1.60	0.32
N_2O release (kg CO_2-eq/kg FPC-milk)	0.25	0.22	0.17	0.13
Cow performance:				
FPC-milk[2] (kg/cow/d)	14.9	14.4	15.2	14.4
DMI[3] (kg/cow/d)	16.0	15.7	16.5	15.8
Feed efficiency (kg FPC-milk/kg DMI)	0.91	0.89	0.90	0.89

[1]1st, 2nd, 3rd and 4th quartile = farms with low, medium-low, medium-high and high levels of N fertilizer applied per hectare of pasture grazed by lactating cows, respectively.
[2]FPC-milk = fat-and-protein-corrected milk production (IDF 2010).
[3]DMI = Dry matter intake estimated from NRC (2001) equation.

Table 7. Estimated greenhouse gas [methane (CH_4) + nitrous oxide (N_2O)] emissions and fertilizer practices for specialized dairy farms (n=104) ranked in quartiles according to partial carbon footprint[1].

Parameter	Partial carbon footprint (CH_4 + N_2O) quartile[1] (kg CO_2-eq/kg FPC-milk)			
	4th	3rd	2nd	1st
	0.82	0.62	0.56	0.47
Source of emissions (%)				
CH_4 from enteric fermentation	63	68	71	75
N_2O from fertilizer[2] on grazed pasture	15	10	7	5
N_2O from fertilizer[2] on cut-and-carry grass	1	0	1	0
N_2O from manure[3] on grazed pasture	21	21	21	20
Farm characteristics:				
Lactating cows (head)	47.7	54.9	51.3	69.7
Grazing + cut-and-carry pastures (ha)	24.9	19.8	18.8	21.8
Stocking rate[4] (cows/ha)	2.4	3.1	3.3	3.5
Elevation (masl)	392	481	854	1123
Precipitation (mm/yr)	3,500	3,572	3,632	3,277
Temperature (°C)	24.5	24.1	22.1	20.6

[1]1st, 2nd, 3rd and 4th quartile = farms with low, medium-low, medium-high and high levels of CH_4 + N_2O emissions expressed as CO_2-eq/kg fat-and-protein-corrected milk produced (FPC-milk), respectively.
[2]Emissions associated with commercial N fertilizer application.
[3]Emissions associated with manure (feces + urine) from cows during grazing.
[4]Average stocking rates (average lactating cow numbers divided by average area of grazing + cut-and-carry pastures) differed substantially because of large standard deviations for some quartiles for lactating cow numbers or area of grazing + cut-and-carry pastures.

Partial carbon footprint

The sum of estimated CH_4 and N_2O emissions for each farm was determined giving an average of 617 g CO_2-eq/cow/d, but ranged from 383 to 1,021 g CO_2-eq/kg of FPC-milk. When farms were stratified into groups according to total emissions, average emissions were 467 g in the low emitting group, 556 g in the medium-low emitting group, 624 g in the medium-high emitting group and 821 g CO_2-eq/kg FPC-milk in the high emitting group. These emissions should not be interpreted as a complete carbon footprint of milk production by specialized dairy farms of Dos Pinos, but rather a first step towards a partial farm gate carbon footprint. In 2010, the Food and Agriculture Organization of the United Nations reported average emissions of CO_2-eq/kg FPC-milk at farm gate, ranging from 1,300 to 7,500 g from various regions of the world (FAO 2010). Although our study included some of the most important sources of greenhouse gas emissions from within the farm (enteric CH_4 plus N_2O from fertilizer and manure deposition from cows in the pasture), there were not enough reliable data to estimate other sources of emissions, which were not accounted for in this study. Some of these sources include:

- Emissions associated with the production and transport of feed ingredients such as concentrates, by-product feeds and purchased forages (hay and bagged silage).
- Emissions associated with collection, storage and application of manure deposited by cows in the barn, which are recognized as an important source of greenhouse gases (Dong et al. 2006).
- Emissions of CO_2 associated with the use of fuel and electricity on the farm.

What farm-related factors are associated with high and low overall GHG emissions? All management factors discussed above for estimated CH_4 and N_2O emissions also influence overall GHG emissions. Table 7 shows the percentage of estimated emissions associated with each of the 4 sources of GHG included in this study. Overall, CH_4 emissions accounted for 69%, N_2O emissions from commercial fertilizer applied to grazed pasture accounted for 9%, N_2O emissions from commercial fertilizer applied to cut-and-carry pasture accounted for 1%, and N_2O emissions from manure deposited by the cows during grazing accounted for 21% of the estimated emissions in this study. Partial carbon footprint was reduced on farms that had a lower proportion of N_2O emissions from commercial fertilizer applied on grazed pasture, but a greater proportion of enteric emissions, reflecting the "dilution effect" of greater milk production (Table 7). In contrast, contribution of N_2O emissions from manure deposited by the cows during grazing did not vary whether the farm was a high emitter or a low emitter. Although there were large variations in stocking rates within each quartile, data in Table 7 indicated that the partial carbon footprint was lower on farms with higher stocking rates (lactating cows/ha of grazed and cut-and-carry pastures), which most likely reflected more intensive feeding management practices (milk production, feed consumption, feed conversion efficiency and N use efficiency).

In addition, data in Table 7 indicated a strong relationship between the partial carbon footprint and farm characteristics that are fixed (conditions that may not be changed such as elevation) or unlikely to change in the near future unless there is a main restructuring of the farm (buying/selling of land or building new facilities to accommodate a larger herd size). Partial carbon footprint was reduced with higher elevation and lower average temperature (Table 7). This relationship is likely to reflect changes in feeding and fertilizer practices in distinct ecosystem zones of the country (see Figure 1), but the data from this study were insufficient to explore whether these fixed characteristics may have a direct effect on partial carbon footprint. Current knowledge, however, suggests that both CH_4 emissions from dairy cows and N_2O emissions from pasture may be influenced in part by bio-physical (soil type) and environmental (temperature and humidity) conditions. For example, heat stress in dairy cattle, which depends upon a combination of temperature and relative humidity, reduces feed consumption and milk production. Thus, higher temperature and humidity in the lowland humid tropical regions may have a substantial effect on CH_4 emissions from cows. In regard to N_2O emissions, recent research by Montenegro (2013) suggested that the redistribution of water and nitrates (a precursor of N_2O) due to the topography (slope of the terrain) had a substantial impact on emissions from highly fertilized pasture.

Discussion and Conclusions

The estimates of CH_4 and N_2O emissions we have derived are dependent on the assumptions in the particular equations we used. Thus none of the values presented here should be considered as definitive for the actual amounts of these gases released from dairy farms in Costa Rica, i.e. the partial carbon footprint. However, the principles, which have been demonstrated, indicate where the areas of greater release exist and where effort should focus to reduce emissions.

While this study estimated emissions of CH_4 and N_2O from specific sources within the farm, additional data are needed for a complete assessment of the carbon footprint of milk production in specialized dairy farms of Costa Rica, or for a complete life cycle assessment. Implications and recommendations made here relate only to reducing emissions from the specific sources within the farm (farm gate boundaries). We found that decisions made by dairy producers, which determine the strategies of feeding lactating cows, have a substantial impact on CH_4 emissions per kg FPC-milk produced on the farm. The fact that lower CH_4 emissions/kg milk were observed on farms with high-producing cows consuming rations with lower neutral detergent fiber concentrations and higher amounts of concentrates highlights the importance of focusing on high production per cow. The key factor influencing CH_4 emissions was the amount of milk produced per cow, which was strongly controlled by the amount of concentrate fed. Higher feed conversion efficiency (more kg milk produced/kg of feed consumed) was a key factor in reducing CH_4 emissions per kg FPC-milk produced on the farm. We could not detect any effect of hours spent in pasture on grass intake or CH_4 emissions.

Future approaches to reducing farm gate emissions of CH_4 in Costa Rican specialized dairy farms may include the following:

- Inclusion of dietary fats in rations. Dietary fats are known to reduce CH_4 emissions from dairy cows (Knapp et al. 2014). As long as concentration of dietary fats does not exceed approximately 6.5% of dry matter intake, no negative impacts are expected but additional benefits may result through increased energy intake and alleviation of heat stress (because the processing of fat by the cow produces less heat than processing of fiber).
- Inclusion of adequate amounts of concentrates in the diet. High quality concentrate feeds also increase the energy (and protein) supply. Compared with an all-grass diet, the inclusion of an adequate amount of concentrate should increase feed conversion efficiency and reduce CH_4 emissions per kg FPC-milk produced on the farm.
- Increased forage digestibility would be an alternative approach to providing cows with a higher quality (i.e. energy) diet without reducing the proportion of forage in the diet (and thus avoiding increasing dependence on imported grains). Forage digestibility varies with plant maturity at the time of harvest (for preserved forages) or at the time of grazing (for pasture-based systems).
- Focusing on genetic improvement of dairy herds by recording individual milk yields of cows and using sires from high-producing dams to place selection pressure on high yield potential would produce replacement animals with the potential to produce higher yields if fed correctly.

This study demonstrated also that decisions made by the farmer, e.g. relating to fertilizing of grazed pastures and cut-and-carry pastures, have substantial impacts on estimated N_2O emissions per kg FPC-milk produced on the farm. While estimated higher N_2O emissions were associated with higher amounts of commercial fertilizer applied, the main source of N_2O estimated in this study was manure (feces + urine) deposited by the cows during the grazing period. These emissions were influenced by a number of factors including: hours of grazing, feed intake (which influenced the amount of manure produced per day), crude protein content of the ration and the level of milk production of the cows. Most of these factors are determinants of N use efficiency (conversion of dietary N into milk N). Since any N consumed by a cow but not used for milk production is excreted as manure (urine plus feces), this study has shown that N_2O emissions were reduced substantially on farms that achieved higher N use efficiency.

As opposed to increasing concentrate feeding, which increased CH_4 emissions per cow, but decreased CH_4 emissions per kg of milk produced on the farm, increasing N fertilizer levels had detrimental effects on emissions of both N_2O/ha pasture and N_2O/kg milk produced on the farm. Thus to avoid unnecessary N_2O emissions, researchers and technical support groups in Costa Rica should:

- Develop standards for applying commercial N fertilizer to pasture designed not to maximize grass production, but rather to produce an economical and high-quality feed for lactating dairy cows, while not leading to excessive N_2O release; and
- Develop practices to quantify and account for organic N deposited by the cows during the grazing periods.

A combination of these 2 factors would allow the reduction of commercial fertilizer usage and would reduce the greenhouse gas emissions associated with the synthesis, transport and application of commercial fertilizer on pasture.

Recommendations for future studies

Future studies should focus on data collection for evaluation of sources of emissions not included in this study, particularly emissions from manure deposited by cows in the barn (collection, storage and land application) and emissions associated with the production and transport of feed ingredients such as concentrates, by-product feedstuffs and purchased forages (hay and bagged silage). Additional areas would be factors influencing feed efficiency and N use efficiency on Costa Rican dairy farms as a means to improve productivity, reduce emissions and possibly increase profitability. Given the relationships observed in this study between estimated greenhouse gas emissions and the biophysical locale of the farm (elevation, rainfall and temperature), future research should focus on identifying "unavoidable" and "acceptable" levels of emissions as well as emissions that can be reduced with proper management techniques. Finally, data should be collected to determine the actual and potential carbon sequestration (e.g. in tree plantations) or carbon offsets (e.g. bio-digestion) on Costa Rican dairy farms. The road toward carbon neutrality should include measures and practices to reduce emissions of greenhouse gases, promote carbon sequestration and offset (avoid) emissions within and outside the farm gates.

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References

Aguerre MJ; Wattiaux MA; Powell JM; Broderick GA; Arndt C. 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. DOI: 10.3168/jds.2010-4011

Bolaños R; Watson V; Tosi J. 1999. Mapa ecológico de Costa Rica (Zonas de Vida): Según el sistema de clasificación de zonas de vida del mundo de L.R. Holdridge. Edited 2005 by V. Jiménez S. Centro Científico Tropical, San José, Costa Rica. (Available at: http://goo.gl/QuHXZs).

Chacón AR; Montenegro J; Sasa J. 2009. Inventario nacional de gases con efecto invernadero y absorción de carbono en Costa Rica en el 2000 y 2005. Instituto Metereológico Nacional, San José, Costa Rica.

de Klein C; Novoa RSA; Ogle S; Smith KA; Rochette P; Wirth TC. 2006. Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. In: IPCC (International Panel on Climate Change), ed. 2006 IPCC guidelines for national greenhouse gas inventories. Volume 4: Agriculture, forestry and other land use. p. 11.1–11.54. (Available at: http://goo.gl/YQPGoX).

Dong H; Mangino J; McAllister TA; Hatfield JL; Johnson DE; Lassey KR; Lima MA de; Romanovskaya A. 2006. Chapter 10: Emissions from livestock and manure management. In: IPCC (International Panel on Climate Change), ed. 2006 IPCC guidelines for national greenhouse gas inventories. Volume 4: Agriculture, forestry and other land use. p. 10.1–10.87. (Available at: http://goo.gl/1IhOK1).

FAO (Food and Agriculture Organization of the United Nations). 2010. Greenhouse gas emissions from the dairy sector: A life cycle assessment. A report prepared by Food and Agriculture Organization of the United Nations, Animal Production and Health Division. FAO, Rome, Italy. (Available at: http://goo.gl/6Ydd).

Hijmans RJ; Cameron SE; Parra JL; Jones PG; Jarvis A. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25:1965–1978. DOI: 10.1002/joc.1276

Holdridge LR. 1967. Life zone ecology. Revised Edn. Tropical Science Center, San José, Costa Rica. (Available at: http://goo.gl/bpgKOx).

IDF (International Dairy Federation). 2010. A common carbon footprint approach for dairy: The IDF guide to standard lifecycle assessment methodology for the dairy sector. Bulletin No. 445. International Dairy Federation, Brussels, Belgium. (Available at: http://goo.gl/iEF8Co).

IPCC (International Panel on Climate Change). 2016. Organization. www.ipcc.ch/organization/organization.shtml (accessed April 2016).

Knapp JR.; Laur GL; Vadas PA; Weiss WP; Tricarico JM. 2014. Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. Journal of Dairy Science 97:3231–3261. DOI: 10.3168/jds.2013-7234

Martin C; Morgavi DP; Doreau M. 2010. Methane mitigation in ruminants: From microbe to the farm scale. Animal 4:351−365. DOI: 10.1017/S1751731109990620

Mertens DR. 1997. Creating a system for meeting the fiber requirements of dairy cows. Journal of Dairy Science 80:1463−1481. DOI: 10.3168/jds.s0022-0302(97)76075-2

Montenegro J. 2013. Influencia de diferentes condiciones de suelo en la emisión de óxido nitroso en una gramínea bajo pastoreo intensivo. In: Montenegro J, ed. El cambio climático y el sector agropecuario costarricense: Contribuyendo con la mitigación. Instituto Nacional de Innovación y Transferencia en Tecnología Agropecuaria (INTA) and Instituto Meteorológico Nacional (IMN), Ministerio de Ambiente y Energía (MINAE), San José, Costa Rica. p. 93−107.

Montenegro J; Herrera J. 2013. Determinación de la emisión de óxido nitroso en pasto kikuyo (*Kikuyuochloa clandestina*) bajo pastoreo: Efecto de diferentes fuentes y niveles de nitrógeno. Tópicos Meteorológicos y Oceanográficos 12(1):9–21. (Available at: https://goo.gl/L23iCl).

Moraes LE; Strathe AB; Fadel JG; Casper DP; Kebreab E. 2014. Prediction of enteric methane emissions from cattle. Global Change Biology 20:2140−2148. DOI: 10.1111/gcb.12471

NRC (National Research Council). 2001. Nutrient requirements of dairy cattle. 7th revised Edn. National Academy Press, Washington, DC, USA. (Available at: https://goo.gl/U67Owh).

Olmos Colmenero JJ; Broderick GA. 2006. Effect of dietary crude protein concentration on milk production and nitrogen utilization in lactating dairy cows. Journal of Dairy Science 89:1704−1712. DOI: 10.3168/jds.S0022-0302(06)72238-X

Ortiz-Malvassi E. 2009. Atlas digital de Costa Rica 2008. http://repositoriotec.tec.ac.cr/handle/2238/3140 (accessed September 2016).

Ramin M; Huhtanen P. 2013. Development of equations for predicting methane emissions from ruminants. Journal of Dairy Science 96:2476−2493. DOI: 10.3168/jds.2012-6095

Villalobos L; Sánchez JM. 2010. Evaluación agronómica y nutricional del pasto ryegrass perenne tetraploide (*Lolium perenne*) producido en lecherías de las zonas altas de Costa Rica. I. Producción de biomasa y fenología. Agronomía Costarricense 34:31−42. (Available at: http://goo.gl/tnMpQc).

Villalobos L; Arce J; WingChing R. 2013. Producción de biomasa y costos de producción de pastos estrella africana (*Cynodon nlemfuensis*), kikuyu (*Kikuyuocloa clandestina*) y ryegrass perenne (*Lolium perenne*) en lecherías de Costa Rica. Agronomía Costarricense 27:91−103. (Available at: https://goo.gl/UnD8Nb).

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