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ESTRATEGIAS DE INTENSIFICACIÓN EN SISTEMAS DE PRODUCCIÓN DE LECHE Y SUS IMPACTOS AMBIENTALES

por

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RESUMEN

La intensificación de los sistemas de producción de leche, o el proceso de aumentar la productividad total de leche (kg) por vaca o por unidad de área de tierra, se puede lograr a través de varias estrategias, como aumentar la carga animal, el consumo de concentrados y forraje. Sin embargo, se debate si la intensificación está asociada con una mayor eficiencia económica y/o ambiental. En Uruguay, el aumento de la producción de leche de los sistemas basados en pasturas ha implicado un mayor uso de concentrados e insumos, lo que condujo a un mayor impacto ambiental. Por lo general, estos impactos se expresan por unidad de producto, lo que no refleja el impacto local por unidad de tierra. El objetivo del trabajo fue analizar las estrategias de intensificación de los sistemas de producción de leche en Uruguay y explorar los impactos tanto productivos, económicos y ambientales que se generan a partir de una serie de indicadores como los Gases de Efecto Invernadero (GEI), consumo de energía fósil, ecotoxicidad y potencial de eutrofización. Si bien el aumento en el uso de concentrados en las dietas se asoció con una mayor productividad de leche y, un incremento en el producto económico bruto y los costos totales de insumos, estas se asociaron negativamente de manera consistente con la eficiencia energética expresada en $MJ.l^{-1}$. Los sistemas lecheros con mayor producción tuvieron menores GEI pero mayor ecotoxicidad por kg de leche que los sistemas con menor producción de leche. Los resultados sugieren que aumentar la productividad de la leche no redujo los impactos ambientales por kg y aumentó los impactos por ha. Para determinar los impactos ambientales que se generan a partir de la intensificación de los sistemas de producción lecheros es más relevante analizar las estrategia de alimentación (mayor proporcion de pasturas o de concentrado) y la cantidad de agroquímicos, que las variables asociadas a la productividad.

Palabras clave: ganaderia de leche, modelos ambientales, alimentos concentrados, pastoreo

SUMMARY

Intensification of milk production systems, or the process of increasing total milk productivity (kg) per cow or per unit of land area, can be achieved through various strategies, such as increasing animal load, consumption of concentrates and forage. However, it is debated whether intensification is associated with greater economic and / or environmental efficiency. In Uruguay, increased milk production from pasture-based systems has implied greater use of concentrates and inputs, leading to greater environmental impact. In general, these impacts are expressed per unit of product, which does not reflect the local impact per unit of land. The objective of the work was to analyze the intensification strategies of the milk production systems in Uruguay and explore the productive, economic and environmental impacts that are generated from a series of indicators such as Greenhouse Gases (GHG), consumption of fossil energy, ecotoxicity and eutrophication potential. Although the increase in the use of concentrates in the diets was associated with higher milk productivity and an increase in the gross economic product and total input costs, these were consistently negatively associated with energy efficiency expressed in $MJ.l^{-1}$. The dairy systems with higher production had lower GHG but higher ecotoxicity per kg of milk than the systems with lower milk production. The results suggest that increasing milk productivity did not reduce environmental impacts per kg and increased impacts per ha. To determine the environmental impacts that are generated from the intensification of dairy production systems, it is more relevant to analyze the feeding strategy (greater proportion of pastures or concentrate) and the amount of agrochemicals, than the variables associated with productivity.

Keywords: dairy farming, environmental models, concentrated feed, grazing

1. INTRODUCCIÓN

En Uruguay la producción obtenida en predios con lechería comercial durante el año 2018 se estimó en 2.237 millones de litros, con un aporte de 660 millones de dólares, representando un 11 % del PIB del aporte del sector agropecuario (DIEA 2019a) siendo este un sector importante dentro de la economía del país. Es por ello que identificar sistemas económicamente viables con una estrategia de producción pastoril, que genere el menor impacto ambiental es de suma importancia.

En Uruguay los sistemas de producción lecheros al ser especializados, su principal fuente de ingreso se genera a través de la venta de leche. Por lo tanto, un aumento en la producción de leche puede conducir a un aumento en la rentabilidad del predio. Para simplificar, se puede decir que hay dos maneras para lograr un aumento en la producción de leche: aumentando la carga animal o aumentando la producción de leche por vaca. El aumento de la carga animal es el más utilizado, ya que el productor solo requiere capital para comprar más vacas. Es por ello que cuando la eficiencia de utilización de pasturas es baja, el incremento en la carga generalmente determina mejoras en la eficiencia de cosecha, en la productividad del sistema y en el resultado económico (Baudracco et al. 2010).

Pero la producción de leche basada en cantidades crecientes de concentrado se ha descrito como curvilínea, es decir el aumento de leche por kilogramo de concentrado disminuye a medida que aumenta la cantidad de concentrado (Kellaway y Harrington 2004). Algunos trabajos han descrito que el uso de concentrados aumentó la producción de leche; sin embargo, el aumento fue mayor cuando las vacas pastaban con una asignación de pastura baja y no hubo respuesta cuando la pastura de alta calidad estaba disponible ad libitum (Bargo et al. 2002; Kellaway y Harrington 2004). De igual forma se conoce poco sobre los efectos ambientales que estos procesos de intensificación conllevan.

Existen numerosos conceptos acerca de la intensificación, pero en su mayoría concuerdan que es la producción de más unidades de salida dado un nivel de insumos, es decir el aumento de la leche o de la carne por unidad de superficie (Herrero et al. 2016). La intensificación se puede lograr a través de varias estrategias, una de ellas es la intensificación convencional, que se ha logrado a partir de aumentar la cantidad de ganado lechero por hectárea, la adquisición de ganado genéticamente mejorado y el aumento de los concentrados en las dietas (Caviglia-Harris 2005) respaldado por el uso de insumos como fertilizantes, herbicidas y combustible para aumentar los rendimientos de grano y forraje (Alexandratos y Bruinsma 2012). Esta estrategia de intensificación basada en los insumos y el alto uso de energía fósil, puede provocar graves impactos ambientales por mayores emisiones de Gases de Efecto Invernadero por combustibles fósiles, emisiones de fertilizantes nitrogenados y metano entérico por unidad de superficie (Meul et al. 2007). La erosión del suelo, la lixiviación de nutrientes, la contaminación del agua y la eutrofización de los cuerpos de agua, son otros impactos ambientales asociados con la intensificación convencional basada en un mayor uso de cultivos e insumos anuales (Modernel et al. 2013; Picasso et al. 2014).

En respuesta a los problemas ambientales y sociales generados por este modelo, la intensificación ecológica (Tittonell 2014) aparece como una alternativa sostenible, integrando indicadores ambientales y agregando valor a los productos mediante tecnologías de proceso que explotan los mecanismos ecológicos que subyacen a la productividad, la estabilidad y la resiliencia de los sistemas productivos pastoriles (Hanson et al. 1998; Parker et al. 1992). Esta alternativa busca desarrollar sistemas de producción sostenibles que reduzcan el consumo de energía fósil y generen mejores resultados económicos (Dalgaard et al. 2001; McLaughlin et al. 2000), lo que también genera menores emisiones de gases de efecto invernadero por unidad de superficie (Dalgaard et al. 2001; Doucet 2008; Meul et al. 2007) por lo tanto, contribuyen a mitigar el cambio climático.

1.1. JUSTIFICACIÓN E IMPORTANCIA

En Uruguay, los sistemas de producción lecheros son de base pastoril, y existe una tendencia a la intensificación productiva, mostrando aumentos significativos con referencia años anteriores, tanto en litros por hectárea producidos como en valores de rendimiento por vaca masa y por vaca en ordeñe (DIEA 2019b). Este proceso de intensificación, se ha dado por el incremento en el uso de alimentos concentrados, el aumento de la producción y utilización del forraje, mientras que la cosecha directa de forraje por parte de los animales ha permanecido sin cambios significativos (Chilibroste et al. 2012). Sin embargo, las trayectorias tecnológicas de los sistemas lecheros no son homogéneas, existiendo incorporación continua y creciente de tecnologías que permitieron un sustancial incremento de la productividad para mantener el ingreso, generando diferentes procesos que afectaron la producción y el medio ambiente (Durán y Lamanna 2009). Existe información de variables aisladas como el uso de energía fósil (Llanos et al. 2018), eutrofización (Perdomo et al. 2001; Pacheco et al. 2012), ecotoxicidad (Miguez 2017; Furley et al. 2018) y la huella de carbono (Lizarralde et al. 2014), pero es de suma importancia una evaluación conjunta de los múltiples impactos ambientales que los sistemas lecheros generan.

Este estudio contribuirá a aportar elementos técnicos para avanzar en la sustentabilidad ambiental de los sistemas lecheros de Uruguay al mismo tiempo que se mantiene o mejora la productividad, ofreciendo a los productores y los responsables políticos del país una visión conjunta del impacto ambiental, económico y productivo de los sistemas de producción de leche.

1.2. OBJETIVOS

El objetivo general de este trabajo es analizar los efectos económicos, ambientales, productivos segun diferentes estrategias de producción basadas en la proporción de pasturas y de alimentos concentrados utilizados en el sistema productivo.

Los objetivos específicos planteados son:

1. Identificar diferentes estrategias de intensificación en sistemas de producción de leche evaluando la relación entre la productividad, el uso de energía fósil y el resultado económico, a partir del estudio de una muestra representativa de establecimientos lecheros remitentes a la industria.

2. Estimar el uso de energía fósil, las emisiones de gases de efecto invernadero, la ecotoxicidad, el potencial de eutrofización, por unidad de área y por unidad de producto

3. Realizar índices integrados de los impactos ambientales globales y locales en función de la productividad por hectárea.

1.3. HIPÓTESIS

Para abordar los objetivos planteados, se postularon una serie de hipótesis, detalladas a continuación.

1. La intensificación de los sistemas de producción de leche asociados con el uso de concentrados y reservas, ha aumentado la productividad, incrementando el costo económico y el consumo de energía fósil.

2. Los sistemas de producción de leche con mayor producción tendrán un menor impacto ambiental a nivel global (emisiones de Gases Efecto Invernadero) por kg de leche que los sistemas con menor producción de leche.

3. Los sistemas de producción de leche con mayor producción tendrán un mayor impacto ambiental a nivel local por hectárea de tierra que los sistemas con menor producción de leche.

1.4. ORGANIZACIÓN DE LA TESIS

Esta tesis comprende un marco teórico (Capítulo 2) sobre los sistemas de producción lecheros y la evaluación de impactos ambientales. Luego siguen dos capítulos con resultados presentados con formato de artículo científico.

El Capítulo 3 comprende el estudio de las variables económicas, productivas y consumo de energía fósil, analizando la relación existente entre ellas. Para ello se usó el registro de datos productivos y económicos de 30 predios lecheros que remiten su leche a CONAPROLE, la principal industria láctea del país, para el año fiscal 2009–2010. Los predios están ubicados en la región sur de Uruguay, en los departamentos de Colonia, San José, Canelones y Maldonado. Los predios se incluyeron en el estudio porque tenían registros confiables y una variabilidad importante en productividad de leche, a fin de explorar una mayor diversidad de estrategias de producción.

En el Capítulo 4 se evaluó los impactos ambientales a partir de una serie de indicadores como lo son: Gases de Efecto Invernadero, consumo de energía fósil, ecotoxicidad, potencial de eutrofización, a través de una encuesta nacional realizada en 2014 por asesores técnicos del Instituto Nacional de Leche de Uruguay (INALE), utilizando una base de datos de 277 predios lecheros. La información encuestada incluyó identificación del predio, datos demográficos de los productores, producción de ganado y leche, manejo reproductivo, uso de la tierra y producción de reservas, compra de alimentos, contrato de servicios de maquinaria (labranza, siembra, fumigación y cosecha), dosis de agroquímicos utilizados, maquinaria propia equipos y venta de servicios, infraestructura de ordeño y tratamiento de efluentes, recursos humanos y tecnología de forraje y ensilaje. Los predios muestreados se ubicaron en los departamentos de Canelones, Colonia, Flores, Florida, Paysandú, Río Negro, San José y Soriano, que representan el 91% de la de la leche remitida, el 89% del rodeo de vacas, el 86% de los predios y el 83% del área lechera en Uruguay (INALE 2014).

En el Capítulo 5 se presenta la discusión general de la tesis, a partir de una síntesis de los resultados más importantes de ambos capítulos, haciendo foco en la intensificación productiva y los impactos ambientales que se derivan. Además se analizan las estrategias productivas utilizadas y la aplicación de este estudio para el análisis ambiental de los sistemas de produccion lecheros.

2. MARCO TEÓRICO

El sector ganadero a nivel mundial está cambiando rápidamente asociado al proceso de globalización y la creciente demanda de alimentos de origen animal, impulsado por el crecimiento de la población y el cambio en los patrones de consumo humano, con un incremento del consumo de proteína de origen animal (FAO 2020). Además, existe una creciente presión en el sector ganadero basado en un mercado con restricciones en las emisiones de carbono, la mitigación de la contaminación del agua, degradación de las tierras y pérdida de biodiversidad, que impulsa al sector ganadero a gestionar los sistemas producción de una manera sostenible ambientalmente. Pero hay grandes diferencias en la forma en que se gestionan los sistemas productivos, en especial los sistemas de producción lecheros. Necesitamos desarrollar una buena comprensión de las diferencias entre los sistemas de producción para poder ayudar a los productores ganaderos a adaptarse a un clima cambiante y mitigar los impactos ambientales.

En el caso de los sistemas de producción en América del Sur, la base de producción es predominantemente pastoril, con niveles variables de suplementación y reservas forrajeras (mayoritariamente producidos fuera del establecimiento) (Franzluebbers, Sawchik yTaboada 2014; Ostrowski y Deblitz 2001; Baudracco et al. 2014). La intensificación de los sistemas lecheros asociada al uso de concentrados y reservas, ha permitido aumentar la productividad de leche con efectos variables sobre el costo económico (IDF 2018), la eficiencia energética, emisión de gases de efecto invernadero, contaminación de las aguas, erosión y biodiversidad (Gerber y Steinfeld 2010). Es por ello que si se pudiera mejorar la eficiencia y la productividad de leche, mediante el aumento del consumo en cantidad y calidad de los alimentos, disminuyendo el uso de agroquímicos, conservando la calidad del suelo y conservando la biodiversidad, para poder aumentar la eficiencia reproductiva e incrementar las ganancias económicas, podría dar lugar a generar sistemas más sustentables (Altieri y Nicholls 2007).

El Analisis de Ciclo de Vida (IPCC 2006) es adecuado para evaluar los impactos ambientales de la producción de leche. De igual modo es necesario la creación o ajuste de los modelos para las mediciones de estos impactos ambientales que deben ser adecuados a las condiciones de cada país.

2.1. PRODUCCIÓN DE LECHE

La producción mundial de leche de vaca para el 2014 fue estimada en 802,2 millones de toneladas, la misma ha crecido un 2,3% cada año en promedio desde el 2000 (IDF 2018). En comparación con otros animales lecheros, la vaca presenta muchas ventajas en términos de facilidad de ordeño, tamaño de la ubre para almacenar leche y el rendimiento de la leche. Hay muchas más vacas lecheras en los países en desarrollo que en los países desarrollados, pero los animales en los países en desarrollo a menudo tienen menores rendimientos de leche por baja producción y lactancias más cortas. El bajo rendimiento de los animales en sistemas a pequeña escala en los países en desarrollo es el resultado de factores como el clima (alta temperatura ambiente, humedad), alimentos de baja calidad, bajos niveles de suplementación de concentrados, y bajo potencial genético (FAO 2020).

El desarrollo tecnológico y la dimensión e infraestructura de los establecimientos productores de leche no son uniformes en América Latina, presentando una gran diversidad en los sistemas ganaderos, que van desde muy baja productividad hasta muy alta productividad (Ostrowski y Deblitz 2001). Los sistemas de producción son pastoriles con suplementación de silajes de cultivos de verano (Argentina, Brasil, Uruguay) o silaje de pasto (Chile) adicionado con concentrados ó granos comprados o de producción propia. La productividad abarca desde 1.500 litros/vaca/ año hasta los 7.300 litros/vaca/año con modelos de alimentación más intensiva, de igual forma encontramos sistemas con una carga animal de 0,7 y 1,3 vacas totales por hectárea (FAO, IDF e IFCN 2014).

En el caso de Uruguay la producción obtenida en predios lecheros durante el año 2018 se estimó en 2.237 millones de litros, existiendo una variación positiva con respecto años anteriores, tanto en litros por hectárea producidos como en valores de rendimiento por vaca masa y por vaca en ordeñe (DIEA 2019b), sin embargo existe una notoria disminución en la superficie, asociada a diferentes procesos como cambio de rubro y perdida de pequeños productores.

2.2. SISTEMAS DE PRODUCCIÓN

Los sistemas de producción ganadera, en especial los sistemas lecheros pueden realizarse de distintas formas, incluso se han realizado varios intentos para proporcionar clasificaciones, que pueden diferenciarse de acuerdo al grado en que el ganado se integra con la producción de cultivos, el tipo de animal, la fuente de alimento o la región agroecológica. El método de categorización de Seré et al. (1995) es quizás el más conocido y el más adoptado. Estos autores clasifican la producción ganadera de rumiantes y no rumiantes en 11 sistemas principales que se dividen en tres categorías:

Sistemas mixtos de cultivo y ganadería: la mayor parte de la carne y la leche de rumiantes producidos a nivel mundial proviene de estos sistemas, pero como categoría es poco precisa. Los sistemas mixtos son aquellos en los que menos del 90% de la Materia Seca proviene de las pasturas (el resto proviene de subproductos de los cultivos, residuos, cosechas y granos alimenticios). Claramente, un predio donde el ganado obtiene el 89% de su alimento de pasturas prediales y el 11% de los alimentos preparados comercialmente; y uno donde el 89% de la fuente de alimento consiste en alimentos comerciales y residuos de cultivos y solo el 11% del pasto será muy diferente. Sin embargo, ambos son sistemas técnicamente mixtos.

Sistemas sin tierra: a menudo denominados sistemas industrializados o confinados, esta categoría representa sistemas exclusivamente ganaderos en los que menos del 10% de la Materia Seca se produce en el predio. El alimento se prepara comercialmente y consiste en cereales y oleaginosas. Sin embargo, los animales criados con este método pueden pasar los primeros 6 a 8 meses de su vida en sistemas a pastoreo, y una vez confinados pueden ser alimentados con pasturas en forma de ensilaje.

Sistemas pastoriles: en estos sistemas, más del 90% de la Materia Seca proviene de pastizales, pastos, forrajes anuales y alimentos comprados, y menos del 10% del valor total de la producción proviene de actividades agrícolas no ganaderas. Este 10% puede provenir de suplementos, como por ejemplo, en la estación seca, los animales pueden recibir heno, melaza u otros suplementos. Esta amplia definición abarca grandes variaciones, desde animales que pastan en escasez de hierba de matorral en el África subsahariana, hasta ganado irlandés criado en pastos exuberantes de una mezcla de raigrás,trébol y fertilizados.

La característica definitoria de los sistemas a pastoreo es que el animal se cría y produce, comiendo pasturas en pie. Los sistemas de pastoriles están impulsados por una combinación de factores interconectados y dinámicos: demográficos, económicos, científicos y tecnológicos, culturales y sociales, así como políticos, institucionales y ambientales (Godde et al. 2018), pudiendo incluir otras clasificaciones como:

Intensificación de los sistemas de pastoreo: cambio hacia sistemas de pastoreo que produzcan más del producto deseado por unidad de recurso utilizada (por ejemplo, capital, mano de obra, tierra). Godde et al. (2018) hace hincapié en los procesos de intensificación que apuntan a aumentar la producción de alimentos por unidad de área debido al desafío tópico de la seguridad alimentaria y la competencia por la tierra.

Extensificación de sistemas de pastoreo: cambio hacia sistemas de pastoreo menos intensivos.

Expansión de los sistemas de pastoreo: Aumentos del área de tierra bajo sistemas de pastoreo debido a la conversión de otros tipos de sistemas de tierra.

2.2.1. Estrategias de los sistemas de producción e impacto ambiental

Los sistemas lecheros intensivos enfrentan riesgos cada vez mayores para su sostenibilidad debido a su alta dependencia de insumos externos, lo que resulta en consecuencias ambientales, económicas y sociales negativas (CIAT 2015). En contraste, se han reportado beneficios en los sistemas lecheros alternativos que involucran menor uso de insumos externos, debido al uso de ciertas prácticas basadas en el uso de pasturas, rotaciones de cultivos y asociación de cultivos. En un meta-análisis presentado por White et al. (2013) sobre los efectos de pasturas mejoradas y su manejo, para analizar los cambios sociales, económicos y ambientales, encontró que las pasturas mejoradas proporcionan beneficios sociales al mejorar el bienestar de las personas, los hogares y las comunidades. A nivel de predio, se documentan cambios de las propiedades físicas, químicas y biológicas que pueden resultar en la mejora de la calidad del suelo, mayor infiltración de agua, y requisitos reducidos de fertilizantes (Ayarza et al. 2007). Schultze-Kraft et al. (2018) demostramos que las leguminosas forrajeras tienen un potencial considerable para aumentar la productividad de los sistemas ganaderos basados en forrajes, al tiempo que brindan beneficios al medio ambiente. Los beneficios ambientales, comprenden efectos positivos sobre: la conservación del suelo y las propiedades químicas, físicas y biológicas del suelo; balance de agua; mitigación del calentamiento global y de la contaminación de las aguas subterráneas; ahorro de energía fósil; biodiversidad funcional (suelo, entomofauna); y rehabilitación de tierras degradadas. Peters et al. (2013) revisó el potencial de las pasturas mejoradas bien manejados para mitigar las emisiones de GEI, comparando los sistemas basados en pasturas con los sistemas de engorde a corral, y concluyó que la huella ecológica de los sistemas basados en pasturas era menor que la de los corrales de engorda.En un sentido puramente físico, la sostenibilidad se ha definido como la capacidad de un proceso o estado que se puede mantener en condiciones particulares durante un período de tiempo determinado, sin quedarse sin los recursos que necesita o generar resultados que de una forma u otra pueden reducir la actividad(Spedding 1995). De esta manera, Olesen, et al. (2000) señala que los sistemas de producción sostenibles requiere que se tengan en cuenta las preocupaciones ambientales y sociales y, por lo tanto, es necesaria una prioridad ética de valores distintos a los económicos a corto plazo y de mercado.

Para el caso de los productores de leche, la identificación de la mejor estrategia de intensificación parece ser difícil, algunos atribuyen mejores performances ambientales a los sistemas de bajos insumos (Belflower et al. 2012; O'Brien et al. 2012), otros asociados a los sistemas más intensivos (Alvarez et al. 2008; Refsgaard, et al. 1998; Thomassen et al. 2008)

A nivel mundial, los aumentos de la productividad ganadera en el pasado reciente han sido impulsados principalmente por la ciencia y la tecnología, los avances científicos y tecnológicos en la cría, la nutrición y la salud animal seguirán contribuyendo a aumentar la producción potencial y aumentar la eficiencia y las ganancias genéticas (Thornton 2010). La demanda de productos pecuarios, particularmente en los países desarrollados, podría estar fuertemente moderada por factores socioeconómicos tales como preocupaciones por la salud humana y valores socioculturales cambiantes (Thornton 2010). Además, en los sistemas de pastoreo, la eficiencia de pastoreo podría desempeñar un papel central en la mitigación de las emisiones de los Gases de Efecto Invernadero (Herrero et al. 2013). En sistemas lecheros un aumento en el suministro de concentrado sin el uso eficiente de los pastos no proporciona una reducción en la huella de carbono (Lizarralde et al. 2014).

La respuesta de mayor producción de leche por unidad de alimento concentrado parece seguir la ley de los rendimientos decrecientes, en el que después de un cierto nivel de la suplementación cada unidad adicional de concentrado se traducirá en un aumento de menos de una unidad de producción de leche (Reis y Combs 2000). Dependiendo de la proporción de concentrado en la dieta de la vaca, el impacto ambiental de la producción puede variar debido a los procesos para producir concentrados que consumen más energía que los proceso para producir forraje, y en los sistemas lecheros alternativos generalmente consumen un poco menos de energía que la agricultura intensiva (Guignard et al. 2009; O'Brien et al. 2012). Esto se debe principalmente a que el origen de los forrajes para la ganadería alternativa, debe ser producido en el predio, así como el uso más bajo o ningún uso de minerales fertilizantes.

2.3. IMPACTOS AMBIENTALES

Es importante evaluar primero los efectos de los cambios en los sistemas de producción de leche sobre los impactos ambientales antes de considerar las opciones de mitigación. El Análisis de Ciclo de Vida es adecuado para las evaluaciones ambientales (IPCC 2006) y se ha utilizado para evaluar losimpactos ambientales de la producción de leche.

Hay dos formas de realizar un Análisis de Ciclo de Vida: los consecuentes y por atribuciones (Thomassen et al. 2008). Los consecuentes apuntan a cuantificar las consecuencias ambientales de un cambio en un sistema de producción, o un cambio en la demanda del producto. La mayoría de los estudios de Análisis de Ciclo de Vida en los sistemas agropecuarios utilizan el de atribuciones, cuyo objetivo es cuantificar el impacto ambiental del producto principal de un sistema, por ejemplo, en los sistemas ganaderos se miden los litros de leche y los kilos de carne. La distinción entre ambas metodologías se desarrolló en el proceso de resolver los debates metodológicos sobre problemas de asignación. Por lo tanto, existe una fuerte conexión entre la elección de cómo manejar los co-productos. Un argumento para utilizar la asignación es que el valor de los co-productos representa el factor causal del proceso de producción (Thomassen et al. 2008). Los resultados de los estudios de Análisis de Ciclo de Vida a menudo no pueden compararse directamente debido a las diferencias en las metodológicas (De Vries y De Boer 2010), por lo que es importante saber distinguir ambos modelos para poder hacer evaluaciones claras y precisas.

Los aspectos que se discuten en los sistemas de producción de leche son diversos, existiendo diferentes estrategias aplicadas por los productores que repercuten en la producción y sustentabilidad de los predios, como alimentación, genética, salud y manejo. Pero el debate general dentro de los conceptos anteriormente señalados pasa principalmente por discutir y conocer bien los siguientes aspectos ambientales:

• El balance entre emisión de Gases de Efecto Invernadero y el secuestro de carbono: en los últimos años se han realizado varias investigaciones con referencia a las emisiones de Gases de Efecto Invernadero generados por la ganadería, los más destacados son los informes publicados por la FAO. En este estudio hace referencia que la ganadería contribuye con 7.1 Gt $CO_{2\text{-eq}}$ o 18% de las emisiones antropogénicas globales de gases de efecto invernadero, y a muchos otros problemas ambientales (Steinfeld et al. 2006), otro informe publicado por Gerbert et al (2013) hace referencia la ganadería representa el 14.5 por ciento de las emisiones de Gases de Efecto Invernadero inducidas por el hombre, aseverando que el sector ganadero juega un papel importante en el cambio climático. Si bien es conocido que los sistemas ganaderos son una fuente de emisión de CO_2, CH_4 y N_2O, se discute que hay sistemas que pueden generar secuestro de carbono en las pasturas, siendo parcial o completamente compensado por lo que emite todo el sistema. Además es importante conocer cuánto se emite y las estrategias que existen de mitigar la emisión de metano (Montes et al. 2013).

• El rol del ciclo de Nitrógeno: Los sistemas ganaderos son una fuente de N_2O que es un potente gas de efecto invernadero, pero también juegan un rol importante en el reciclado de nutrientes, siendo utilizada por las plantas nuevamente para su crecimiento. El inconveniente es que es capaz de causar múltiples problemas ambientales dependiendo de la vía química que se convierta. Una de estas vías conduce al óxido nitroso que representa el 29 % de los Gases de efecto invernadero producidos por los rumiantes, debido a que es 310 veces mayor su potencial de calentamiento global que el CO_2 (IPCC 2007), siendo este generado por microorganismos durante los procesos de nitrificación y desnitrificación (de compuestos nitrogenados) en los suelos de pastizales y pasturas. El otro punto a tener en cuenta es que los organismos vivos son "ineficientes" en su uso de nitrógeno, lo que genera un ciclo de nitrógeno con pérdidas. Las plantas absorben parte del nitrógeno disponible; el resto permanece en el suelo. Esto significa que las generaciones posteriores de plantas pueden utilizarlo, pero también que, dependiendo del clima, los suelos y la temperatura, el nitrógeno puede transformarse en N_2O, o bien en formas que causan la contaminación del suelo y el agua (IPCC 2007).

• Sistemas de pastoreo y cambio del uso del suelo comparado con monocultivos intensivos: Los sistemas de pastoreo ocupan una gran área de tierra, preservan la vegetación natural y almacenan carbono

El cambio en el uso de la tierra, principalmente la deforestación, es la segunda fuente más grande de emisiones antropogénicas de CO_2 y provoca una reducción neta del almacenamiento de carbono en los ecosistemas terrestres, así como otros impactos ambientales como la pérdida de biodiversidad (IPCC 2013). En América Latina, el pastoreo es uno de los principales uso que se le da a las tierras deforestadas, un ejemplo es la deforestación en la Amazonia, siendo ésta una de las regiones del planeta mas afectada por el cambio del uso de la tierra (Graesser et al. 2015).

2.3.1. Estudios de impactos ambientales en sistemas lecheros

Hasta el presente, la mayoría de los estudios han analizado los impactos ambientales a partir de estudios de caso en lugar de usar datos representativos de los predios lecheros a nivel nacional, lo que limita el rango de sistemas evaluados y la capacidad de hacer relaciones. Aunque los resultados de los indicadores individuales son informativos y relevantes, es necesario también disponer de indicadores simples, y sinteticos, que permitan identificar sistemas óptimos de manera holística (Rogge 2012; Wendling et al. 2018). Si bien hay mucho debate sobre los métodos para sopesar los múltiples criterios debido a que los gobiernos, investigadores o partes interesadas, pueden intentar medir lo mismo de diferentes maneras, lo que da como resultado datos que no son comparables entre países o tiempo. Esto conlleva a falta de información verificable sobre los pesos verdaderos para los indicadores múltiples, lo que hace que no esté del todo claro qué pesos asignar a las variables. Los datos deben medirse utilizando una metodología establecida, revisada por pares por la comunidad científica o respaldada por una organización internacional. Sin embargo, los indicadores integrados ayudan a rastrear las tendencias a lo largo del tiempo, resaltar los éxitos y fracasos de las políticas e identificar las mejores prácticas (Wendling et al. 2018)

La mayoría de los estudios existentes se han realizado en países desarrollados con un número limitado de estudios que incluye a países en vías de desarrollo como el realizado por Herrero et al. (2013) que muestra datos en Latinoamerica, o el de Hagemann et al. (2011) que muestran datos de países latinoamericanos. Tambien existen trabajos que hacen análisis de variables ambientales específicas como es el caso de los Gases de Efecto Invernadero en distintos países como en Brasil (Primavesi et al. 2004; Cunha et al 2016; Dall-Orsoletta et al. 2016), o en Argentina

(Garcia et al. 2013; Denoia 2008). Otros trabajos plantean la necesidad de más información a nivel regional de los impactos ambientales que ejerce la ganadería en la zona, y no de estimar en función de parámetros realizados en países desarrollados debido a que las condiciones de manejo, estrategias de alimentación, clima, temperatura, raza. son diferentes (Cederberg et al. 2013; Picasso et al. 2014 Lizarralde et al. 2014).

2.3.2. Impactos ambientales globales y locales

Para definir y medir el impacto ambiental de los sistemas de producción lecheros nos basamos en el concepto de sostenibilidad ambiental, abordado anteriormente. Muchos trabajos basados en el Análisis de Ciclo de Vida tienen como objetivo incorporar indicadores de impacto ambiental, asignando una capacidad de carga tanto local como global. El impacto ambiental global de un predio se define como su contribución relativa al cumplimiento de la capacidad de carga del ecosistema global, y se mide por medio de un indicador de intensidad ambiental durante toda la producción. El impacto ambiental local puede entenderse como el impacto ambiental máximo por unidad de área de tierra agrícola que puede ser sostenido por el ecosistema local (Repar et al. 2016). Por lo tanto, el desempeño ambiental local se mide por medio de un indicador basado en el área. La implementación de indicadores ambiental locales y globales por separado, en lugar de usarlos sin distinguirlos en términos conceptuales, proporciona una evaluación más adecuada del desempeño ambiental de los predios, así como una mejor base para la comparación entre ellos. Además, elimina el riesgo de trasladar los problemas ambientales de la escala local a la global o viceversa.

Otras investigaciones han demostrado que a menudo existen diferencias entre estos impactos ambientales globales (p. Ej., Uso de energía fósil y emisiones de gases de efecto invernadero) y locales (p. Ej., Ecotoxicidad y eutrofización del agua) en los sistemas ganaderos (Modernel et al. 2013; Modernel et al. 2018). Los impactos ambientales de relevancia global se expresan por unidad de producto (es decir, kg de leche) mientras que los impactos ambientales de relevancia local se expresan por unidad de superficie (Repar et al. 2017; Flaten et al. 2018), y estos dos pueden proporcionar resultados diferentes (Picasso et al. 2014). Repar et al. (2016) encontraron correlaciones negativas entre el impacto ambiental local y global, lo que implica que una mejora del impacto ambiental global probablemente conducirá a un deterioro del desempeño ambiental local y viceversa. Por lo tanto, una evaluación integral de los impactos ambientales debe tener en cuenta múltiples indicadores por unidad de producto y por unidad de superficie, así como una visión holística del sistema de producción.

A continuación se presentan los dos artículos publicados en ingles en revistas científicas pertenecientes a los capítulos 3 y 4 de esta tesis. El Capítulo 3 comprende el estudio de las variables económicas, productivas y consumo de energía fósil, analizando la relación existente entre ellas y el Capítulo 4 se evaluó los impactos ambientales a partir de una serie de indicadores como lo son: Gases de Efecto Invernadero, consumo de energía fósil, ecotoxicidad, potencial de eutrofización. Ambos artículos tienen una base de datos diferente, pero ambas de gran confiabilidad y representativas para los objetivos trazados en los dos artículos.

3. ENERGY AND ECONOMIC EFFICIENCY IN GRAZING DAIRY SYSTEMS UNDER ALTERNATIVE INTENSIFICATION STRATEGIES[1]

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3.1. ABSTRACT

The intensification of dairy systems, or the process of increasing milk productivity per unit of land area, can be achieved through various strategies. However, it is debated whether intensification is associated with increased economic and/or environmental efficiency. The aim of this study was to identify alternative intensification strategies for grazing dairy systems and evaluate their economic and energy efficiency. A model for calculating energy inputs and outputs was applied to 30 dairy farms with reliable production and economic records in Uruguay, spanning a wide range of farm features. Milk productivity averaged 3819 l.ha$_{-1}$ year$_{-1}$ (ranging from 1512 to 6942), intake of concentrate averaged 0.25 kg l^{-1} of milk (ranging from 0.03 to 0.38), fossil energy use averaged 3.96 MJ kg^{-1} (ranging from 1.9 to 9.1) and farm net income averaged 317 U$D ha^{-1} year^{-1} (ranging from 136 to 748). Using a numerical classification procedure, four farm clusters that represent different technological, production, and efficiency situations for grazing dairy farms were identified, associated with the differential use of pastures and concentrates. Although increasing used of concentrates in diets was associated with higher milk productivity, and sometimes higher economic performance, it was consistently negatively associated with energy efficiency. Dairy farms with a higher proportion of pasture consumption achieved higher efficiency of utilization of feed concentrates (higher kg milk/kg concentrate) and thus used less fossil energy per liter of milk. These results suggest that sustainable intensification of grazing dairy systems should rely on efficient utilization of pastures rather than just increasing concentrate intake.

Keywords: Farming systems, Grazing, Energy efficiency, Forages Ecoefficiency

3.2. INTRODUCTION

The growth in global population and income has increased demand for food production and consumption, especially animal proteins (Ranganathan et al., 2016).

The intensification of livestock systems is the process of increasing milk or meat productivity per unit of land area, and it has been proposed as the necessary path to sustain humanity (Herrero et al., 2016). Intensification can be achieved through various strategies. Conventional intensification of livestock production systems has been achieved by increasing the number of dairy cattle per hectare of land, the acquisition of genetically improved cattle, and the increase in concentrates in the diets (Caviglia-Harris, 2005) supported by use of inputs such as fertilizers, pesticides, and fuel to increase grain and forage yields (Alexandratos and Bruinsma, 2012). This intensification strategy based on inputs and high fossil energy use can result in serious environmental impacts. The emission of greenhouse gases by combustion of fossil fuels, emissions from nitrogen fertilizers, and enteric methane from cattle significantly contributes to climate change (Meul et al., 2007). Soil erosion, nutrient leaching, water contamination and eutrophication of water bodies, are other environmental impacts associated with conventional intensification based on higher use of annual crops and inputs (Modernel et al., 2013; Picasso et al., 2014).

The rising costs of livestock inputs and low prices of products entailed a lower profit margin for producers. Increased productivity through investment in technology (inputs and capital) was the way to increase production and improve the profitability of farming systems (Dartt et al., 1999; Somda et al., 2005). In response to environmental and social problems generated by this model, ecological intensification (Tittonell, 2014), appears as a sustainable alternative, integrating environmental indicators and adding value to the products, through exploiting ecological mechanisms that underlie the productivity, stability and resilience, including the balance between feedstuff (grains) and pasture management (Hanson et al., 1998; Parker et al., 1992). This alternative seeks to develop sustainable production systems that reduce consumption of fossil energy and generate better economic results (Dalgaard et al., 2001; McLaughlin et al., 2000), which would also result in lower emissions of greenhouse gases (Dalgaard et al., 2001; Doucet, 2008; Meul et al., 2007) therefore mitigating climate change.

Grazing is the basis of the dairy production systems in South America, with varying levels of supplementation with conserved forages (Franzluebbers et al., 2014; Ostrowski and Deblitz, 2001). The intensification of dairy systems associated with the use of concentrates and reserves, has increased the productivity of milk with variable effects on the economic cost and energy efficiency. Identifying the best strategy for intensification in dairy appears to be difficult, because while some studies document improved environmental performance of low input systems, other studies contradict this. For instance, Meul et al. (2007) showed reduced energy input from a lower use of fertilizers and concentrates, with 25 % increase in milk productivity per ha through a higher milk productivity per cow and a higher stocking rate. Several studies agree that fuel, electricity, fertilizer and animal feed together represent the main part of the total energy consumption (Cederberg and Flysjo, 2004; Cederberg and Mattsson, 2000; Kraatz, 2012; O'Brien et al., 2012; Rabier et al., 2010). Oudshoorn et al. (2011) concluded that minimizing local as well as global environmental impacts did not have an economic trade-off. On the other hand, Alvarez et al. (2008) showed that intensive farms produced at a lower average total cost and presented greater levels of efficiency than extensive farms. Basset-Mens et al. (2009) demonstrated that the high inputs systems can be more profitable when milk price is high and maize silage cost is low but the low inputs systems are more profitable when milk price is low and maize silage cost is high. Therefore, it appears from the previous literature that the relationship between environmental and economic efficiency depends on the dairy systems considered, the region, and the management practices analyzed. The aim of this study was to identify different intensification strategies for grazing dairy farms and evaluate the relationship between productivity, fossil energy consumption per kg of milk (FECK) and economic outcome, using a group of Uruguay dairy farms as a case study.

3.3. MATERIALS AND METHODS

3.3.1. Dairy systems database

In Uruguay, dairy cows are usually fed sown pastures of mixtures of grasses and legumes year round, supplementing the diet with corn grain and/or sorghum and silage to maintain milk production during winter when pasture production is poor. These silages are generally produced on the same dairy farm. During milking time, the cows are fed concentrates to satisfy the nutritional requirements of their expected level of production. Dairy cattle are predominantly Holstein breed. The 2009–10 average productivity of Uruguay was 4334 l cow^{-1} and 2410 l ha^{-1} per hectare (DIEA, 2010), and the average annual precipitation in the area was 1100 mm with a maximum temperature of 27° Celsius and minimum 4° Celsius (INIA, 2010).

The farms database for this study was obtained from the productive and economic records of 30 dairy farms remitting their milk to CONAPROLE, the major dairy industry of the country, for the 2009–2010 fiscal year, which was an average climate year. Farms were located in the southern region of Uruguay, in the departments of Colonia, San José, Canelones, and Maldonado. Farms were included in the study because they had reliable records and a broad range of milk productivity, in order to explore the diversity of production strategies. Data from milk productivity per hectare (MPH, l ha^{-1}), milk productivity per cow (MPC, l cow^{-1}), stocking rate (SR, cow ha^{-1}), herd efficiency (number of milking cows/total stock, HE, %), total dry matter intake per cow per year (DMI, kg cow^{-1}), concentrate intake per liter of milk (CL, kg l^{-1}), concentrate intake per cow per year (CC, kg cow^{-1}), proportion of the total intake from concentrate (PIC), proportion of the total intake from pasture (PIP), and proportion of the total intake from silage (PIS), were obtained from the records of each producer. Actual pasture yields were not recorded, and pasture intake per cow is estimated by difference.

3.3.2. Energy model

The Agroenergía model proposed by Llanos et al. (2013) was used for energy calculations. The model estimates energy inputs and outputs using energy coefficients from international literature and also local coefficients adjusted to the conditions of Uruguay. The model accounts for the input of fossil energy used in different activities within the farm (feed production in pasture or annual crops and feed purchased outside the farm, Figure 1). The model uses the Hetz and Barrios (1997) methodology to quantify the energy costs of machinery operations per unit area (MJ ha^{-1}), with the coefficients presented by ASAE (1993) and Fluck (1985), for the use of machinery for feed production produced within the farm and bought off farm. For activities within the farm and feed purchased off-farm fossil energy from fuels and agrochemicals (fertilizers, herbicides, and pesticides) were added (Figure 1). Fossil energy consumption per liter of milk (FECL, $MJ.l^{-1}$) was calculated.

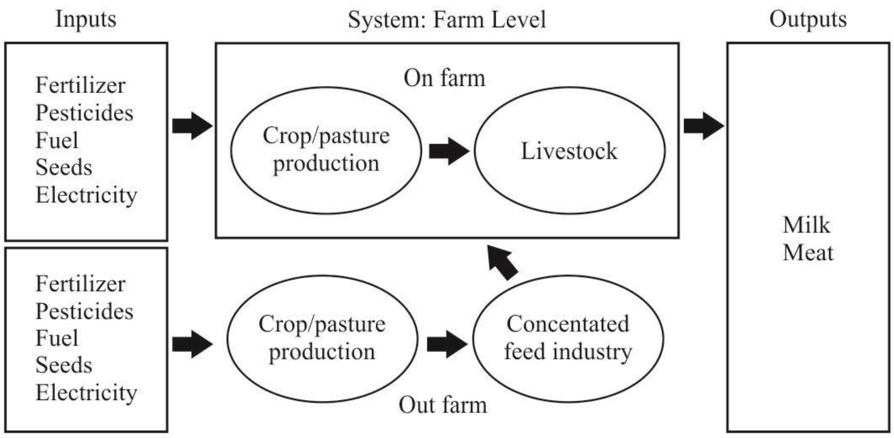

Figure 1: Model of the system used to quantify the energy inputs and outputs at the farm level.

As outputs the model considers the energy value of milk and meat. The energy value of milk (EM) was calculated from the equation based on the percentages of fat (% F) and milk protein (% P) for each farm: EM= 40.72 (% F)

+22.65 (% P) + 102.7 (Tyrrell and Reid, 1965). The energy value of the meat was calculated from the weight of the different tissues by animal category (García, 1997) and the tissue energy value proposed by Marletta and Carnovale (2000). The main energy parameters used in the Agroenergía model are presented in Table 1 (Llanos et al., 2013).

In order to compare alternative systems of production with previous studies in the literature, our results were transformed to the units of 1 kg energy corrected milk (ECM) and 1 kg fat and protein corrected milk (FPCM) by the following equations: kg ECM = kg milk [0.25 + 0.122 (% F) + 0.077 (% P)] (Sjaunja et al., 1990) and kg FPCM = kg milk [0.337 + 0.116 (% F) + 0.06 (% P)] (FAO, 2010).

Table 1: Criteria and energy coefficients used to calculate fossil energy included in the model Agroenergía (Llanos et al., 2013).

Input (unit)	Energy (MJ/unit)	Criteria	Reference
Diesel (l)	38.50	Calorific value of diesel used in Uruguay, analyzed by bomb calorimeter.	(Ministerio de Industria Energía y Minería, 2010)
Electricity (kW.h)	1.6	Represents 31% of electricity produced from petroleum	(Ministerio de Industria Energía y Minería, 2010)
Herbicides (kg) Insecticides (kg) Fungicides (kg)	266.6 284.8 288.9	Include the formulation of the active compounds in oils, powders or granules, packaging and transport.	(West and Marland, 2002)
Urea (kg) Ammonium nitrate (kg) Mono Ammonium Phosphate (kg) Triple superphosphate (kg)	54 46.6 4.30 7	IFA simplified model uses natural gas as a source of ammonia production (80% of world production).	(Kongshaug, 1998)
Sorghum seeds (kg) Wheat seeds (kg) Corn seeds (kg) Red clover seeds (kg) Ryegrass seeds (kg)	43.5 6.6 53.3 87 27.4	Include cleaning and packaging of the seed. It consists of a 50, 20, and 30% mixture of fuel oil, natural gas and electricity, respectively.	(West and Marland, 2002)

3.3.3. Economic analysis

Farm purchases and sales records were kept by farmers every month, and converted using the monthly dollar exchange rate for fiscal year 2009–2010. The net income per hectare (NI, USD ha^{-1}) was calculated from the gross economic product per hectare (GP, USD ha^{-1}) minus total costs of inputs per hectare (TC, USD ha^{-1}), without accounting for financial interest or land rent. The gross economic product per hectare (GP, USD ha^{-1}) was the sale of milk and meat adjusted at the price of milk and meat using the monthly dollar exchange rate. The total cost of inputs per hectare (TC, USD ha^{-1}) included feed costs, operating costs (electricity, labor, animal health, repair and maintenance of milking equipment) and structural costs (repair and maintenance barn, housing, vehicles and taxes) at the monthly exchange rate. The Input over Output ratio (I/O) was calculated dividing the gross economic product (GP) by total costs of inputs (TC), and represents a measure of economic efficiency.

3.3.4. Statistical analysis

The correlation matrix was calculated with all production, energy and economic variables with two objectives: first to identify collinearity (variables that are highly correlated) before performing the multivariate analysis, and second to identify which variables are most associated with fossil energy use. Principal Component Analysis was conducted using variables that were not collinear to graphically explore the relationship between the variables. The variables included in the analysis were: proportion of total intake from pasture (PIP), net income per hectare (NI), milk productivity per hectare (MPH), concentrate intake per cow per year (CC) and fossil energy consumption per kg of milk (FECK). A numerical classification in clusters was performed using Ward's algorithm and Euclidean distances using the same variables used for the Principal Components Analysis. Analysis of variance (ANOVA) was performed using clusters as classification variable. Groups were considered different for each variable only when the P value for the ANOVA was smaller than 0.05. Tukey multiple comparison tests were conducted for those variables with significant differences detected in the ANOVA, in order to identify which groups were different for each variable. All analyses were performed using Infostat (2012) software.

3.4. RESULTS

The mean and dispersion of the main variables analyzed on 30 dairy farms are shown in Table 2. Milk productivity per hectare (MPH) and milk productivity per cow (MPC) were positively correlated to dietary variables associated of concentrated feed such as concentrate intake per liter of milk (CL), concentrate intake per cow (CC) and proportion of the total intake from concentrate (PIC), but negatively associated with the proportion of total intake from pasture (PIP). Productivity was also positively correlated to economic variables: gross economic product per hectare (GP) and total costs of inputs per hectare (TC) (Table 3).

Gross economic product per hectare (GP) and total costs of inputs per hectare (TC) were positively correlated with dietary variables associated with the use of concentrates such as concentrate intake per liter of milk (CL), concentrate intake per cow per year (CC) and proportion of the total intake from concentrate (PIC) and negatively correlated with proportion of intake from pasture (PIP) (Table 3).

Table 2: Mean, coefficient of variation (CV), minimum (Min) and maximum (Max) of the production, energy and economic variables for 30 grazing dairy farms in southern Uruguay. All variables are calculated for one year.

Variable	Units	Mean	CV (%)	Min	Max
Farm Size	ha	358	94	46	1448
Milk productivity per hectare (MPH)	$l.ha^{-1}.year^{-1}$	3819	38	1512	6942
Milk productivity per cow (MPC)	$l.cow^{-1}.year^{-1}$	5492	21	2758	8581
Stocking rate (SR)	$cow.ha^{-1}$	0.7	28	0.36	1.22
Herd efficiency (HE)	Milking cows/stock	0.58	17	0.35	0.81
Concentrate intake per liter of milk (CL)	$kg.l^{-1}$	0.25	31	0.03	0.38
Total dry matter intake per cow per year (DMI)	$kg.cow^{-1}.year^{-1}$	7701	16	5252	12281
Concentrate intake per cow per year (CC)	$kg.cow^{-1}year^{-1}$	1471	46	95	3385
Proportion of total intake from concentrate (PIC)		0.2	49	0.02	0.54
Proportion of total intake from pasture (PIP)		0.59	24	0.26	0.8
Proportion of total intake from silage (PIS)		0.22	42	0.07	0.37
Net income per hectare (NI)	$USD.ha^{-1}.year^{-1}$	317	41	136	748
Gross economic product per hectare (GP)	$USD.ha^{-1}.year^{-1}$	1140	34	594	2011
Total costs of inputs per hectare (TC)[a]	$USD.ha^{-1}.year^{-1}$	822	40	315	1614
Input over Output ratio (I/O)		0.71	12	0.53	0.85
Fossil energy consumption per kg of milk (FECK)[b]	$MJ.l^{-1}$	3.96	47	1.9	9.12

[a] Production costs per hectare of milk and meat without interest or rent from the farm.

[b] Mega Joule units from Fossil Energy including the use of chemicals, fuel, energy fixed in machinery, agricultural activities within the farm and feed purchased outside the farm, calculated with the model Agroenergía (Llanos et al., 2013)

The Fossil energy consumption per kg of milk (FECK) was positively correlated only with the dietary variables associated with concentrate intake per liter of milk (CL), concentrate intake per cow per year (CC), concentrate intake per liter of milk (CL), and proportion of the total intake from concentrate (PIC) (Table 3). Proportion of intake from pasture (PIP) was negatively correlated with fossil energy consumption per kg of milk (FECK).

Table 3: Pearson correlation coefficient (r, below the diagonal) and the level of significance (P, above the diagonal) for simple linear correlations between productive variables, feed, economic and energy of 30 grazing dairy farms form southern Uruguay. Significant correlation values are shown in bold (P < 0.05).

	MPH	MPC	SR	HE	CL	DMI	CC	PIC	PIP	PIS	NI	GP	TC	I/O	FECK
MPH	1	**<.01**	**<.01**	**<.01**	**<.01**	0,13	**<.01**	**<.01**	**<.01**	**<.01**	**<.01**	**<.01**	**<.01**	0,06	0,26
MPC	**0,72**	1	0,55	**<.01**	**<.01**	**<.01**	**<.01**	**<.01**	**<.01**	0,05	0,02	**<.01**	**<.01**	0,39	0,08
SR	**0,76**	0,11	1	**<.01**	0,46	0,26	0,18	0,09	0,02	0,06	0,12	**<.01**	**<.01**	0,03	0,93
HE	**0,77**	**0,75**	**0,46**	1	**<.01**	0,12	**<.01**	**<.01**	**<.01**	**<.01**	0,16	**<.01**	**<.01**	0,03	0,07
CL	**0,48**	**0,6**	0,14	**0,56**	1	**<.01**	**<.01**	**<.01**	**<.01**	0,18	0,52	**<.01**	**<.01**	0,12	**<.01**
DMI	0,28	**0,66**	-0,21	0,29	**0,53**	1	**<.01**	**<.01**	0,04	0,5	0,91	0,05	0,02	0,4	0,42
CC	**0,72**	**0,85**	0,25	**0,78**	**0,87**	**0,67**	1	**<.01**	**<.01**	0,06	0,2	**<.01**	**<.01**	0,05	**<.01**
PIC	**0,74**	**0,81**	0,32	**0,8**	**0,9**	**0,55**	**0,97**	1	**<.01**	0,04	0,16	**<.01**	**<.01**	0,07	**<.01**
PIP	**-0,71**	**-0,68**	-0,42	**-0,8**	**-0,65**	-0,38	**-0,76**	**-0,8**	1	**<.01**	0,38	**<.01**	**<.01**	0,02	**<.01**
PIS	**0,45**	0,36	0,35	**0,54**	0,25	0,13	0,35	0,38	**-0,86**	1	0,84	0,04	**<.01**	0,08	0,08
NI	**0,5**	0,44	0,29	0,26	0,12	0,02	0,24	0,26	-0,17	0,04	1	**<.01**	0,11	**<.01**	0,78
GP	**0,96**	**0,74**	**0,7**	**0,73**	**0,49**	0,36	**0,73**	**0,72**	**-0,65**	0,39	**0,59**	1	**<.01**	0,14	0,39
TC	**0,94**	**0,7**	**0,71**	**0,76**	**0,52**	0,41	**0,76**	**0,74**	**-0,7**	**0,44**	0,3	**0,95**	1	**<.01**	0,26
I/O	0,35	0,16	0,39	0,39	0,29	0,16	0,36	0,34	-0,41	0,33	**-0,56**	0,28	**0,55**	1	0,09
FECK	0,21	0,32	0,02	0,34	**0,47**	0,15	**0,44**	**0,45**	**-0,47**	0,32	-0,05	0,16	0,21	0,31	1

MPH =milk productivity per hectare; MPC= milk productivity per cow; SR = Stocking rate; HE= herd efficiency; CL=concentrate intake per liter of milk; DMI = total dry matter intake per cow per year; CC = concentrate intake per cow per year; PIC =proportion of total intake from concentrate; PIP =proportion of total intake from pasture; PIS = proportion of total intake from silage; NI =net income per hectare; GP =gross economic product per hectare; TC =total costs of inputs per hectare; I/O =input over Output ratio; FECK = fossil energy consumption per kg of milk.

The two principal components explained 80 % of the total variability of the observations (principal component 1: 57%, and principal component 2: 23%, Figure 2). As the eigenvalues show (Table 4) Principal Component 1 was positively associated with milk productivity per hectare (MPH), and concentrate intake per cow (CC), and negatively associated with proportion of the total intake from pasture (PIP). Principal Component 2 was positively associated with net income per hectare (NI), and negatively associated with fossil energy consumption per kg of milk (FECK).

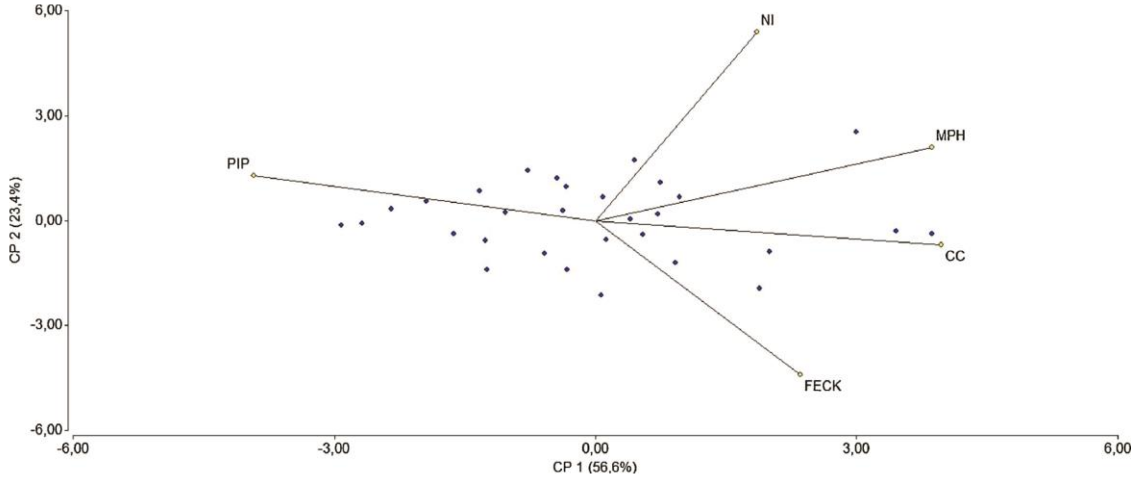

Figure 2: Principal Component Analysis showing five variables (open dots and lines): proportion of the total intake from pasture (PIP), net income per hectare (NI), milk productivity per hectare (MPH), concentrate intake per cow per year (CC) and Fossil energy consumption per kg of milk (FECK) for 30 grazing dairy production systems (closed dots) in Uruguay.

Table 4: Eigenvalues for the principal components 1 and 2 for 30 dairy farms in Uruguay.

Descriptive farm variables	Eigenvalues	
	PC1	PC2
Milk productivity per hectare (MPH, $l.ha^{-1}$)	0,52	0,28
Proportion of the total intake from pasture (PIP)	-0,53	0,17
Concentrate intake per cow per year (CC, $kg.cow^{-1}$)	0,53	-0,09
Net income per hectare (NI)	0,25	0,73
Fossil energy consumption per kg of milk (FECK, $J.kg^{-1}$)	0,32	-0,6

A cluster analysis using these five production, nutritional, economic and energy variables was performed, resulting in four groups (Table 5). Group 1 (G1) was comprised by dairy farms which base their production on the use of pastures with low herd efficiency and low use of concentrates, allowing a low consumption of fossil energy, but low milk productivity per hectare. Group 2 (G2) had higher productivity than the G1 due to increased milk productivity per cow, being associated with greater use of concentrate per liter of milk and concentrate intake per cow per year. Group 3 (G3) had higher milk productivity per hectare by high milk productivity per cow using the same proportion of the total intake from concentrate (PIC) in the diet and a higher stocking rate (SR), obtaining good productive and economic results. Group 4 (G4) has highest indicators of productivity, based on a higher concentrate intake per liter of milk, concentrate intake per cow per year and less proportion of the total intake from pasture, showing an increased consumption of fossil energy consumption per kg of milk, and better economic results than group 1 and 2 but not significantly different than group 3 (Table 5).

Table 5: Means of production, feed, energy and economic variables for four groups of farms obtained by numerical classification of 30 grazing dairy production systems in Uruguay. Means followed by the same letter are not different between groups (Tukey P < 0.05). A significance value for the ANOVA between groups is shown (p-value).

	Units	G1	G2	G3	G4	p-valor
Number of farms (n)	ha	4	9	11	6	
Milk productivity per hectare (MPH)	$l.ha^{-1}.year^{-1}$	2220 c	2880 bc	4258 ab	5484 a	<0.01
Milk productivity per mass cow (MPC)	$l.cow^{-1}.year^{-1}$	4015 c	5144 b	5505 b	6975 a	<0.01
Stocking rate (SR)	$cow.ha^{-1}$	0,59	0,58	0,79	0,78	0,03
Herd efficiency (HE)	Milking cows/stock	0.45 c	0.55 bc	0.59 b	0.70 a	<0.01
Concentrate intake per liter of milk (CL)	$kg.l^{-1}$	0.14 b	0.25 a	0.24 a	0.33 a	<0.01
Total dry matter intake per cow per year (DMI)	$kg.cow^{-1}.year^{-1}$	7410	7633	7231	8858	0,06
Concentrate intake per cow per year (CC)	$kg.cow^{-1}year^{-1}$	639 c	1321 b	1358 b	2455 a	<0.01
Pasture consumed (DM) per ha per year		5845 a	4626 ab	4330 b	3948 b	0,03
Proportion of total intake from concentrate (PIC)		0.08 c	0.17 b	0.19 b	0.30 a	<0.01
Proportion of total intake from pasture (PIP)		0.79 a	0.60 b	0.60 b	0.43 c	<0.01
Proportion of total intake from silage (PIS)		0.13 b	0.22 ab	0.22 ab	0.27 a	0,09
Net income per hectare (NI)	$USD.ha^{-1}.year^{-1}$	230 ab	225 b	386 ab	387 a	<0.01
Gross economic product per hectare (GP)	$USD.ha^{-1}.year^{-1}$	691 c	900 bc	1264 ab	1567 a	<0.01
Total costs of inputs per hectare (TC)[a]	$USD.ha^{-1}.year^{-1}$	461 c	675 bc	878 ab	1179 a	<0.01
Input over Output ratio (I/O)		0,66	0,75	0,68	0,75	0,15
Fossil energy consumption per kg of milk	$MJ\ kg^{-1}$	2.02 c	4.51 ab	2.93 bc	6.33 a	<0.01
Fossil energy consumption per kg of energy corrected milk	$MJ\ kg\ ECM^{-1}$	2.17 c	4.76 ab	3.02 bc	6.57 a	<0.01
Fossil energy consumption per kg of fat and protein corrected milk	$MJ\ kg\ FPCM^{-1}$	2.14 c	4.71 ab	2.99 bc	6.52 a	<0.01

Mega Joule units from Fossil Energy including the use of chemicals, fuels, energy fixed in machinery, agricultural activities within the farm and feed purchased outside the farm calculated with the model Agroenergía (Llanos et al., 2013).

[a] Production costs per hectare of milk and meat without interest or rent from the farm.

3.5. DISCUSSION

Intensification of dairy farms based on increasing the proportion of the total intake from concentrates consistently increased production costs and sometimes (but not always) increased net income per hectare. At the same time this intensification consistently increases fossil energy consumption per unit of milk. On the contrary, farms that use higher proportion of pasture in the diets have a more efficient use of concentrate feed (as the lower the substitution rate the higher the milk response to supplements, Bargo et al., 2003), make less fossil energy use and can achieve good economic income, such as farms from group 3 (Table 5). These results are consistent with those presented by Parker et al. (1992); Dartt et al. (1999); Somda et al. (2005). The milk production response determines whether the use of concentrates is cost effective based on the prices of milk and concentrates. The fat content of milk is reduced when cows are grazing pastures compared with that achieved with concentrated feedstuff, but the economic impact of changes in milk composition depends on the relative prices paid by the milk industry (Parker et al., 1992). In our case there was no difference in net income from fat and protein milk in different groups (data not shown), implying that the increase in energy and protein content of feed concentrate does not outweigh the economic costs obtained in production. However, in order to make an economic assessment, other additional factors, such as increased rates of livestock on the farm, improved pasture utilization, reproduction, duration of lactation should be considered (Bargo et al., 2003).

The finding that fossil energy consumption is positively associated with increased concentrate use, is consistent with previous findings from international literature (Table 6). These studies represent a variety of milk production systems and climatic conditions; hence, the large differences in results across studies. Based on data from two relatively large dairy farms in the west of Sweden, Cederberg and Mattsson (2000) estimated higher energy use in conventional systems versus organic systems (with increased pasture use) with more than double milk production per hectare in the conventional farm versus the organic farm. Another paper by Cederberg and Flysjo (2004) studied 23 dairy farms in the west of Sweden, also obtained similar results. In the Netherlands, Thomassen et al. (2008) found that the energy use of 10 conventional commercial dairy farms was higher than the one of 11 organic dairy farms (Table 6). They concluded that feeding more feed produced on farm, feeding less concentrates, and using no pesticides and artificial fertilizers resulted in a lower energy use per kg FPCM (Thomassen et al., 2008). The results presented by O'Brien et al. (2012) showed that the non-renewable energy use of a confinement dairy farm was almost double the one of an intensively grazed seasonal grass-based dairy system in Ireland (Table 6). In a recently published study, Pagani et al. (2016) compared grain based versus forage based dairy farms in Italy and United States, finding that forage based farms had lower energy use than grain based (Table 6). Therefore, our results agree with previous literature that farms with higher degree of intensification based on concentrated feed use more fossil energy per unit of milk produced.

Table 6: Comparison of cow feed, milk production and energy consumption in different type of production systems for assessment of milk production of selected studies, gathered by functional unit.

Reference	Type of System	Cow Feed	Milk Production	Total Energy	Functional Unit
Cederberg, C., & Flysjo, A. (2004)	Conventional High	601 Kg/cow/year mixed concentrate feed	9460 kg ECM per hectare	2.59	$MJ.l^{-1}$ ECM
	Conventional medium	401 Kg/cow/year mixed concentrate feed	5360 kg ECM per hectare	2.73	$MJ.l^{-1}$ ECM
	Organic	294 Kg/cow/year mixed concentrate feed	5100 kg ECM per hectare	2.10	$MJ.l^{-1}$ ECM
Cederberg, C., & Mattsson, B. (2000).	Conventional	2267 kg grass silage, 687 kg pressed beet pulp, 1531 kg concentrate feed, approx. 350 kg pasture	$7415\ kg.ha^{-1}$	3.55	$MJ.l^{-1}$ ECM
	Organic	1869 kg silage 1355 kg hay, 775 kg pasture, 1000 kg peas, 343 kg concentrate feed	$3297\ kg.ha^{-1}$	2.51	$MJ.l^{-1}$ ECM
Thomassen, M. A., van Calker, K. J., Smits, M. C. J., Iepema, G. L., & de Boer, I. J. M. (2008)	Conventional	The most common concentrate ingredients used in the conventional system, which account for 60%, were maize gluten meal, beet pulp, and palm kernel meal.	7991 kg.cow	5.0	MJ.FPCM
	Organic	The most common concentrate ingredients used in the organic system, which account for 65%, were palm kernel meal, organic wheat grain, organic triticale grain, organic lucerne, and organic lupines	6138 kg.cow	3.1	MJ.FPCM
O'Brien et al. (2012)	Grass	Concentrate 370 kg DM/cow per year and Grass 4093 kg DM/cow per year	6639 kg FPCM/cow per year	2.3	MJ.FPCM

	Confinement	Concentrate 2865 kg DM/cow per year and no Grass	8040 kg FPCM/cow per year	3.9	MJ.FPCM
This study	G1	Concentrate 639 kg.cow^{-1}year^{-1} and 0.79 % from pasture	2129 ECM.ha^{-1}, 3896 FPCM/Cow per year	2,17	MJ.kg ECM
				2,14	MJ.kg FPCM
	G2	Concentrate 1321 kg.cow^{-1}year^{-1} and 0.60 % from pasture	5443 ECM.ha^{-1}, 6987 FPCM/Cow per year	4,76	MJ.kg ECM
				4,71	MJ.kg FPCM
	G3	Concentrate 1358 kg.cow^{-1}year^{-1} and 0.60 % from pasture	4235 ECM.ha^{-1}, 5524 FPCM/Cow per year	3,02	MJ.kg ECM
				2,99	MJ.kg FPCM
	G4	Concentrate 2455 kg.cow^{-1}year^{-1} and 0.43 % from pasture	2811 ECM.ha^{-1}, 5080 FPCM/Cow per year	6,57	MJ.kg ECM
				6,52	MJ.kg FPCM

Although the previous literature has focused on comparisons between confined and pasture based or organic systems, our study focused on analyzing an intensification gradient within grazing dairy systems, which are still the large majority of dairy systems in developing countries. We developed an “intensification trajectory” graph (Figure 3) plotting the environmental performance measured as fossil energy consumption (in the Y axis) versus milk productivity (in the X axis). We added economic performance (net income) and proportion of intake from concentrate as area-sized bubbles in the same plot (Picasso et al., 2017). This intensification trajectory graph is a useful tool to understand the effect of diet changes simultaneously on productivity, environmental, and economic performance. As we move in the X axis from left to right, productivity increases, therefore the production system is under an intensification trajectory. As we move up or down in the Y axis, environmental performance decreases or increases respectively. Therefore, it is possible to identify intensification trajectories with reduced environmental performance, and those with improved environmental performance. For instance, moving from Group 1 to Group 2, the intensification is based in increasing concentrates, but not increasing the stocking rate, which in turn reduces pasture utilization (substitution effect, Bargo et al., 2003). This results in a lack of economic improvement and a reduction in energy efficiency. This is a clear example of intensification based on inputs. On the contrary, when moving from Group 2 to Group 3, the intensification is not based on increasing concentrate, but on making a more efficient use of pastures, though higher (but not excessive) stocking rate. This trajectory increases both economic performance and energy efficiency, based on taking more advantage of the ecological processes like photosynthesis, biological nitrogen fixation in pastures, and optimal grazing. This is a clear example of ecological intensification. By keeping a higher proportion of the intake from pastures, Group 3 systems maintain the lowest fossil energy consumption (similar to Group 1), but achieve much higher productivity and net income per hectare.

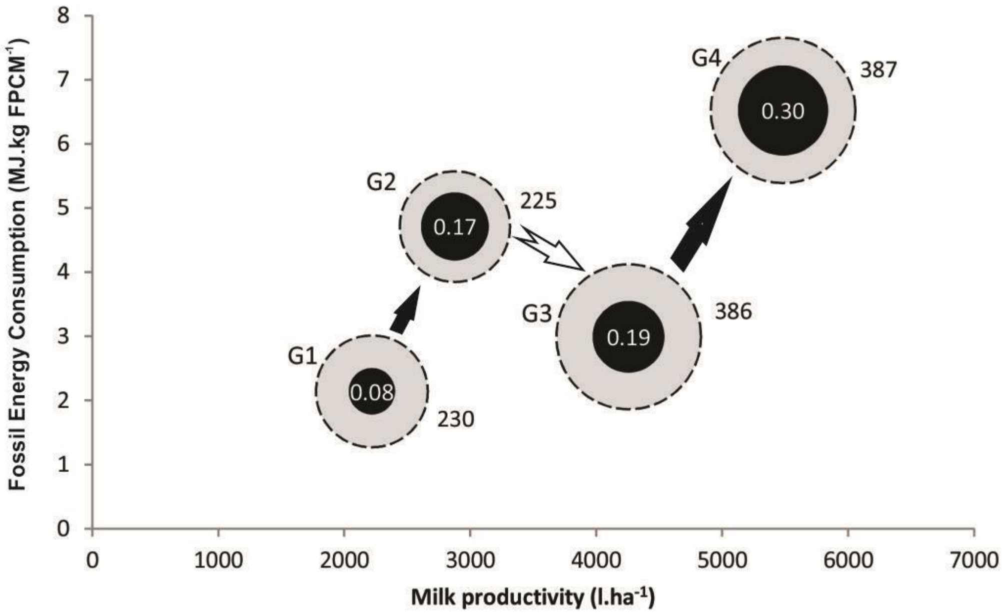

Figure 3: Intensification trajectory graphs for 4 groups of grazing dairy farms in Uruguay: fossil energy consumption (Y axis) vs. milk productivity (X axis). Area of inner black bubbles represents proportion of total intake from concentrate (values in center of the bubble). Area of external grey dotted-border bubbles represents net income per hectare (values outside bubble, in U$S ha^{-1}). Black solid arrows represent input intensification trajectories, while open (white) arrow represents an ecological intensification trajectory.

It is noteworthy that further intensification moving from Group 3 to Group 4, through increased use of concentrates (and again without change in stocking rate), does not increase net income, but drastically reduces energy efficiency. This is another example of input intensification. This again can be explained by the substitution effect of pasture by the concentrates (Bargo et al., 2003). Milk production based on increasing amounts of concentrate has been described as curvilinear with decreasing increments, i.e., the increase in milk per kilogram of concentrate decreases as the amount of concentrate increases (Kellaway and Porta, 1993). Other factors can interfere like the quality of the pastures and the genetic value of cows (Peyraud and Delaby, 2001).

Our findings show that without increasing the pasture use (through for instance, increasing stocking rate) even a moderate increase in concentrates does not lead to increasing net incomes. Groups 2 and 4 (Figure 3) are sub-optimal situations from an economic point of view. Higher use of concentrates provides an opportunity to increase the number of dairy cows, but in the cases analyzed that did not happen. Thus the Group 3 is first of all optimal from an economic point of view, which is the basis for decision making at farms.

A relevant question is whether it is possible to further ecologically intensify dairy systems in Uruguay, and by which means. This requires extending the results of our study to outside the range of the farms we have analyzed, which would be speculative. However, it is reasonable to expect that with increased pasture utilization, via increasing stocking rate, or improved grazing management (e.g., higher forage allowance), it is possible to maintain high levels of pasture in the diet, at high levels of concentrate supplementation also, without substitution of pasture by concentrates. This would increase milk productivity further, while improving energy and economic efficiency. A recent survey of dairy farmers conducted in 2014 by the Uruguayan Dairy Institute (INALE), identified cases of farms which produced over 12000 kg milk.ha-^{1}, with 35% of concentrated feed intake (INALE, com pers.), based on improved high quality pastures. Although not considered in our analyses because of lack of on farm data, ecological intensification relies also in improving forage quality through the use of improved forage species, and forage mixtures including a high proportion of legumes (like Lucerne, birdsfoot trefoil, red clover, or white clover). Optimal forage and grazing management has a central role in improving the productive, economic, and environmental performance of grazing dairy farms.

3.6. CONCLUSIONS

The sustainable intensification of grazing dairy systems, requires an efficient use of pastures and concentrated feed, so that the proportion of the intake from pastures remains high, and the efficiency of use of concentrate (kg milk/kg concentrate) is also high. Moderately increased use of concentrates from very low levels and the stocking rate simultaneously would improve net incomes, and still maintain or improve energy efficiency. This strategy can achieve at the same time high milk productivity, high net economic income, and low use of fossil energy. The use of models for estimating energy and economic indicators of efficiency across a large number of farming systems can help to analyze the sustainability of technological intensification strategies and identify desirable options.

One of the limitations of this study is that the quality of the feed (forage and concentrates) is not considered because of lack of on farm data. Increased feed quality can increase dry matter intake as well as milk production without increasing the consumption of fossil energy. Another limitation in order to discuss the ecological intensification or a more complete sustainability analysis is the lack of other variables of interest such as greenhouse gas emissions, eutrophication, nutrient balance, etc. Furthermore, a more complete economic analysis should include sensitivity to price fluctuations of inputs, including grain and the barrel of oil. More research is needed to design ecological intensification pathways for grazing dairy systems worldwide.

3.7. ACKNOWLEDGEMENTS

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4. DO PASTURE-BASED MIXED DAIRY SYSTEMS WITH HIGHER MILK PRODUCTION HAVE LOWER ENVIRONMENTAL IMPACTS? A URUGUAYAN CASE STUDY [2]

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4.1. ABSTRACT

The increased milk production of pastured-based mixed dairy systems has involved higher use of concentrates and inputs, which led to increased environmental impacts. Usually these impacts are expressed per unit of product, which does not reflect the local impact per unit of land. The objective of this paper was to estimate global and local environmental impacts per kg of milk and per hectare. Fossil energy use, greenhouse gas emissions, water ecotoxicity, nutrient aquatic eutrophication potential, and integrated standardised indices of environmental impacts (IEI) were estimated for 277 pastured-based dairy systems in Uruguay, clustered in seven milk production groups. Dairy systems with higher milk production had lower greenhouse gas emissions but higher ecotoxicity per kg of milk than systems with lower milk production, and the integrated index did not change. In contrast, all the individual indicators and the integrated indices per hectare were higher for the higher milk production systems. The results suggest that increasing milk productivity did not reduce environmental impacts per kg, and increased impacts per ha. Management factors including type of diet (pasture vs concentrate), amount of inputs, and type of grazing system may be more relevant in determining environmental impacts of dairy systems than productivity per se.

Keywords: greenhouse gas emissions, ecotoxicity, eutrophication, energy, dairy farm systems

4.2. INTRODUCTION

Global milk production has been growing 2.2% each year on average since 2000 (IDF 2018), and demand for dairy products will continue to grow during the next 50 years given the increased world population and per capita income worldwide (Britt et al. 2018). Dairy farming systems have increased milk productivity (i.e. total milk production (kg) per cow or per unit of land area) by increasing stocking rates and the consumption of concentrates and forage (Caviglia-Harris 2005; Alvarez et al.

2008; Repar et al. 2016; Flaten et al. 2018). Supplementation with concentrates in pasture-based dairy farms may increase feed consumption and productivity per cow (Bargo et al. 2003), but it may decrease the efficiency of pasture utilization (and the response depends on the cow breed). These changes are sustained by higher inputs use (e.g. fertilizers, pesticides, fossil fuel), and therefore increasing environmental impacts: soil degradation and acidification, nutrient leaching, water contamination, eutrophication, greenhouse gas emissions, among others (Meul et al. 2007; Thomassen 2008; de Klein et al. 2010; Modernel et al. 2013; FAO2016). Therefore, pasture-based dairy farms under adequate grazing strategies, are perceived to have lower environmental impacts than confined systems (Nehring et al. 2009), achieving high milk productivity per cow, and improvements in milk nutritional qualities (Thomet et al. 2011; Provenza et al. 2019).

There is a wide heterogeneity of dairy systems around the world considering diet composition and agroecological regions (Robinson et al. 2011). Mixed rainfed systems are those where more than 10% of DM fed to animals comes from crop by-products or stubble from rainfed land, and they provided 53%of the global milk production (FAO2009). In temperate-humid regions like southern South America, Europe, and New Zealand mixed rainfed humid systems produce milk by feeding on average 50% of DM from forages, 18% of DM from grain, 24% of DM from stover, and 8% from occasional fodder (Herrero et al. 2013).

In Uruguay, mixed rainfed systems are the dominant dairy system, based on grazing native and seeded grass-legume pastures outdoors year-round, with variable levels of concentrate supplementation and preserved forages (Ostrowski and Deblitz 2001; Franzluebbers et al. 2014). These dairy systems are different from New Zealand ones, which rely mostly on fertilized pastures (i.e. 80% of the DM intake comes from pastures, 7% from crops, and 13% from supplements; DairyNZ 2018) and have higher stocking rates (2.8 cows per ha; DairyNZ 2018). However, both countries have pasture-based dairy systems, and have increased their milk production per cow in the last decade at annual rates of 2.4% in New Zealand (DairyNZ 2018) and 2.0% in Uruguay (DIEA 2014).

In Uruguay, the dairy industry is an important economic contributor with great diversity in the farming systems in terms of milk production, productivity, and management (INALE 2014). The dairy herd is 83% Holstein (INALE 2014) and the average weight of the mature cow is 530 kg. Cows with high genetic potential for milk yield, as Holstein cows have, shave a greater milk yield response to concentrate supplementation (Heublein et al. 2017). In general, cow diets are based on grass-legume pastures, supplemented with corn or sorghum silage mainly in winter when pasture production is deficient. Dairy productivity has increased mainly due to a higher use of concentrates and reserves (Astigarraga 2004), through an input intensification process (DIEA 2017; Llanos et al. 2018). The main environmental impacts documented for dairy systems in Uruguay include greenhouse gas emissions (Lizarralde et al. 2014), fossil energy consumption (Llanos et al. 2018) and water quality deterioration and eutrophication due to the presence of nitrate and phosphate in drinking water (Perdomo et al. 2001; DINAMA 2008; MVOTMA 2011; Pacheco et al. 2012). Ecotoxicity studies are one of the priority areas of research for Latin America (Miguez 2017; Furley et al. 2018). The ecotoxicity of pesticide use in dairy systems has not been previously assessed, although the Usetox methodology was used in a previous study in agricultural systems in Uruguay (Darré et al. 2019).

However, the assessment of environmental impacts of dairy systems to date had three main limitations. First, previous research has used farm case studies rather than country level survey data, which limits the range of systems evaluated and ability to make inferences. Second, previous research has shown that trade-offs often exist between global (e.g. fossil energy use and greenhouse gas emissions) and local (e.g. ecotoxicity and water eutrophication) environmental impacts in livestock systems (Modernel et al. 2013, 2018). Environmental impacts of global relevance are expressed per unit of product (i.e. kg of milk) while environmental impacts of local relevance are expressed per unit of land area (Repar et al. 2016; Flaten et al. 2018), and these two metrics may provide different results (Picasso et al. 2014). Therefore, a comprehensive assessment of environmental impacts should account for multiple indicators per unit of product and per unit of land area. Third, although results from individual indicators are informative and relevant, decision makers at farm and country level also demand simple, integrated, composite indicators, that allow them to identify optimal systems in a holistic way (Rogge 2012; Wendling et al. 2018). While there is much debate regarding the methods for weighing and aggregating the individual component variables (Rogge 2012; Greco et al. 2019), integrated indicators help to track trends over time, highlight policy successes and failures, and identify best practices (Wendling et al. 2018).

Therefore, this study aimed to estimate fossil energy use, greenhouse gas emissions, ecotoxicity, eutrophication potential, and integrated indices of global and local environmental impacts of grazing dairy production systems, per unit of area and per unit of product for a large representative sample of dairy farms in Uruguay. The following hypotheses were tested: (1) groups of dairy systems with higher milk production will have lower global environmental impact per kg of milk than systems with lower milk production; (2) groups of dairy systems with higher milk production will have higher local environmental impact per ha of land than systems with lower milk production.

4.3. MATERIALS AND METHODS

4.3.1. Dairy systems and data base

A database of 277 dairy farms from a national survey conducted in 2014 by technical advisors from the Uruguayan National Dairy Institute (Instituto Nacional de la Leche, INALE) was used. The survey was designed to sample a stratified subset of the 3610 dairy farms existing in the country, from the National Agricultural Census from 2011 (DIEA 2011), with an average farm size of 210 ha, an average herd size of 120 cows, producing an average of 1600 litters of milk per day (INALE 2014). The farm land use was on average 42% grass-legume sown pastures, 20% native grasslands, 17% annual forages, and 14% cropland. The information surveyed included farm identification, farmer demographics, livestock stock and milk production, reproductive management, land use and reserves production, feed purchases, contract of machinery services (tillage, planting, spraying and harvesting), doses of agrochemicals used, machinery, own equipment and sale of services, milking and effluent treatment infrastructure, human resources, economic data, and forage and silage technology. Sampled farms were located in the municipalities of Canelones, Colonia, Flores, Florida, Paysandú, Río Negro, San José and Soriano, which account for 91% of milk production, 89% of cow herd, 86% of farms, and the 83% of the dairy area in Uruguay (INALE 2014).

The system limits were defined 'from cradle to farm gate' using a partial Life Cycle Assessment (Cederberg et al. 2013). The estimated environmental impacts were: fossil energy consumption, greenhouse gas emissions, ecotoxicity, nutrient balance, and eutrophication (Figure 1). The inputs were fuel, synthetic fertilisers, herbicides and seeds. The difference between the final and initial stock for grain, hay, silage, was subtracted to the purchased feed of the farm. The environmental impacts associated with the construction of agricultural buildings, machinery, and plastic used on the farm were not included because the information was not available in the survey and in pasture-based dairy systems they have a minor contribution to the results. For instance, an in-depth study of irrigated mixed dairy farms in southern Italy, mostly confined in barns, estimated that building and facilities contributed 5%, and machinery and equipment 12% of total energy consumption of the farms (Todde et al. 2018). In pasture-based dairy systems the contribution of buildings and machinery is expected to be much lower.

The environmental indicators were expressed per kg of milk and per hectare, and the environmental impacts of the feed purchased off-farm were calculated from reference values (Table 1) using country average yields and inputs used for each crop.

A classification of dairy farming systems developed by INALE (2014) was used. Dairy farming systems were typified in four categories based on total annual milk production per farm, then subdivided into seven groups based on milk productivity or forage consumption (Table 2).

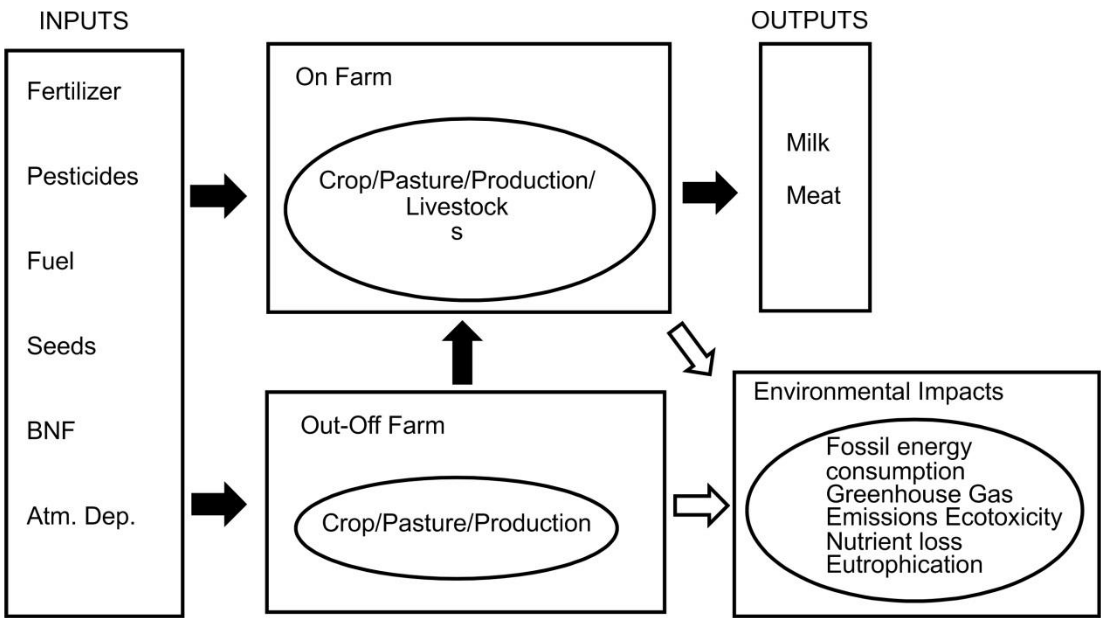

Figure 1. Model representation of the production system and environmental impacts associated with the inputs and outputs at the farm level.

Table 1. Yield for each crop produced off farm (for purchased feed), N and P fertilizer inputs, and estimated fossil energy use, ecotoxicity, eutrophication potential, and N_2O emissions per kg of grain or forage.

Crop	Yield (ton DM ha^{-1})	N (kg kg^{-1})[c]	P (kg kg^{-1})[c]	Fossil energy[d] (MJ kg^{-1})	Ecotoxicity (CTUe)[e]	Eutrophication (PO_{4-eq})[f]	N_2O[g] ($CO_{2-eq}kg^{-1}$)
Sorghum grain	4.0[a]	0.007	0.003	1.53	9.35	0.30	0.01
Grass silage (Ryegrass)	10.0[b]	0.020	0.022	0.80	4.20	4.04	0.08
Alfalfa hay	3.2[b]	0.005	0.010	0.41	2.11	1.19	0.50
Corn grain	4.3[a]	0.006	0.003	3.8	4.86	0.23	2.00
Soybean grain	2.4[a]	0.051	0.007	7.2	1.87	0.32	0.03

[a] Ayala et al. 2010; [b] DIEA 2017; [c] Fertilizer input (kg of N or P from fertilizer per kg of harvested crop). Fertilizers used in the crop rotations: Diammonium phosphate (18-46-0); Mixture II (0-40/41-0+3S); Super concentrated nitrogenous (7-40+5); Superphosphate (0-20/22-0+12s); Urea (46-0-0). Source: www.laguiasata.com; [d] Fossil energy use (MJ) per kg of harvested crop using Agroenergia model (Llanos et al. 2013); [e] Ecotoxicity per kg of harvested crop. [f] Eutrophication potential per kg of harvested crop. [g] N_2O emissions per kg of harvested crop following IPCC (2006a).

Table 2. Definition of the dairy farm system groups based on two criteria (milk production and milk productivity/forage consumption) from the National Dairy Institute (INALE, Uruguay), and percent of farms in the survey from each group (INALE, 2014)

Production category	**Milk production (l $year^{-1}$)**	**Productivity or forage consumption**	**Group**	**% farms**
Low (L)	< 158,000	-	L	7
Medium-Low (ML)	158,000 - 494,000	Milk productivity <3,800 l ha^{-1}	ML1	8
		Milk productivity >3,800 l ha^{-1}	ML2	9
Medium-High (MH)	494,000 -1,030,000	Milk productivity <4,600 l ha^{-1}	MH1	10
		Milk productivity >4,600 l ha^{-1}	MH2	9
High (H)	> 1,030,000	Forage consumption <3,000 kg DM ha^{-1}	H1	31
		Forage consumption >3,000 kg DM ha^{-1}	H2	25

4.3.2. Environmental impacts estimation models

Fossil energy use was estimated following the Agroenergy model described by Llanos et al. (2018). Energy inputs were estimated based on energy coefficients from international literature and also local coefficients adjusted to the conditions of Uruguay accounting for different activities within the farm (feed production in pasture or annual crops and feed purchased outside the farm). Hetz and Barrios (1997) methodology was used to quantify the energy costs of machinery operations per unit area (MJ ha−1), with coefficients by ASAE (1993) and Fluck (1985), for the use of machinery for feed produced within the farm and bought off farm. Fossil energy from fuels and agrochemicals (fertilisers, herbicides, and pesticides) were added also (Supplemental Table S1).

Greenhouse gas emissions were estimated using IPCC tier 2 methodology (IPCC 2006a) and integrated using the global warming potential expressed in kg of CO_2 equivalents for a time horizon of 100 years using the coefficients proposed by Myhre et al. (2013): 1 kg CH_4 = 28 kg CO_2eq, and 1 kg N_2O = 265 kg CO_2eq. For methane emissions from cattle enteric fermentation, average daily feed intake, expressed as gross energy intake, was calculated using the CIPIL Dairy System Model (Astigarraga 2004) for all animal categories on the farm. The CIPIL Dairy System Model integrates the animal and forage production activities linked and bounded by different constraints: structural (arable land area), agronomic (pasture rotation, expected forage yield and digestibility for each pasture type) and animal (total energy requirement).

The net energy was calculated using the equation 10.16 of the IPCC (2006a). The methane conversion factor (Ym) was 6.5% (Supplemental Table S2). Emissions were determined using a methane conversion factor of 1.5%, and a maximum CH_4 production capacity for dairy manure of 0.1 m^3 of CH4 kg^{-1} from daily volatile solids excretion (IPCC 2006a). Direct and indirect emissions of N_2O were calculated following the IPCC (2006b) equations. Emission factor for N of the urine and the manure deposited in the pastures by grazing animals was 0.02 [kg N_2O–N (kg N)$^{-1}$ excreted]; annual amount of synthetic fertiliser N (Table 1) applied to soils (kg N yr^{-1}); emission factor for N volatilized as NH^3 and nitrogen oxide was 0.20 kg of N applied or deposited. Emissions from storage and application of manure were not considered due to lack of information about manure management in the farms. Carbon dioxide emission estimation used IPCC (2006c) guidelines, using energy from tractors and other engine-powered equipment calculated by de Agroenergy model (Llanos et al. 2018), and a conversion factor for diesel fuel of 20.2 kg GJ^{-1}.

The ecotoxicity potential of herbicides for each crop was calculated according to the equation: ICI = Σi (Si × CFi) where: ICI is the Impact Category Indicator for herbicides per crop; Si: is the dose in kg ha−1 of each herbicide used multiplied by the amount of active ingredient present in the herbicide; and CFi: is the characterisation factor, which represents the fraction of species potentially affected per cubic meter in a day and per unit mass of the compound or pollutant emitted (PAF m^3 day kg^{-1} emitted, Rosenbaum et al. 2008). This characterization factors where obtained from the USEtox website (www.usetox.org; Fantke et al. 2017).

The aquatic eutrophication potential (AEP) considers the N and P losses of the system (Brentrup et al. 2004), and the estimation include the amount of a toxic substance (i.e. excess of nutrient N or P) multiplied by a characterization factor of that substance (Rosenbaum et al. 2008). The excess nutrients of the system were calculated as the difference between inputs and outputs (Koelsch and Lesoing 1999). The inputs include the proportion of N and P present in the fertilizers used to produce the crops in the farm (Table 1), and the one that were purchased from other farm, which were multiplied by the fertilizer dose applied in kg ha^{-1}; also, the soy and alfalfa biological fixation and the natural atmospheric deposition of N, in kg ha^{-1} (Carnelos et al. 2014). The outputs were considered as the amount of N and P (kg) of the animal's meat (live weight of the animal) sold from the farms, and the N and P (kg) of the produced milk in the farms (Supplemental Table S3). The characterization factors of the N and P were obtained from the IMPACT 2002+ methodology (N: 0.10; P: 3.06). These characterization factors are expressed in kg $PO_{4\text{-equivalents}}$ kg^{-1} and the AEP in kg $PO_{4\text{-equivalents}}$. The farm dairy effluents were calculated following the DairyNZ (2007) guide.

Finally, integrated Indices of Environmental Impact (IEI) per kg of milk and per ha for each farm were calculated as the sum of the standardized individual environmental indicators (per kg of milk and per ha, respectively): fossil energy use (FE), greenhouse gas emissions (GH), ecotoxicity (ET), aquatic eutrophication potential (AE). These standardized indicators were calculated for each farm as the value of each environmental indicator (i) minus the average value of that indicator for all the farms (X), divided by the standard deviation of that indicator (S). All individual indicators had the same weight in the index. The formula for the IEI was:

IEIi = (FEi − XFE)/SFE + (GHi–XGH)/SGH + (ETi–XET)/SET + (AEi–XAE)/SAE.

In order to asses more local environmental impacts, a second IEI per ha was also calculated using only the two variables that directly impact water quality at the local level: ecotoxicity and aquatic eutrophication potential (IEIw).

4.3.3. Statistical analysis

The environmental indicators differences between groups of farms were assessed by analysis of variance (ANOVA) and multiple comparison tests, after analysing the homogeneity of variance and the residuals by Levene test. Also, various generalized linear mixed models using different variance structures were compared, and results were consistent across models. The InfoStat software was used for the statistical analysis (Di Rienzo et al. 2018). The significance level was α =

0.05. Linear regressions were adjusted for index of environmental impact per kg and per ha against milk productivity per ha and concentrate intake per kg of milk using the mean values for each farm group.

4.4. RESULTS

Of the total fossil energy use, 66 % on average was from activities within the farm while 34 % was from feed purchased off farm. The H1 group had the highest percent of energy used off farm (37 %) and the ML2 group the lowest (26 %). The agrochemicals and fuels (sum of fossil energy use within and off farm) represented 80% of the energy consumed on average. Fossil energy use per kg of milk produced was highest for both high (H1) and low (L, ML1) production groups (Table 3, Figure 2). Fossil energy use per ha was highest for all three higher production groups (MH2, H1 and H2). Fossil energy use per ha increased with productivity per ha (R^2=0.82).

Figure 2. Index of environmental impact for each of the environmental variables per kg of milk and hectare within the 7 groups.

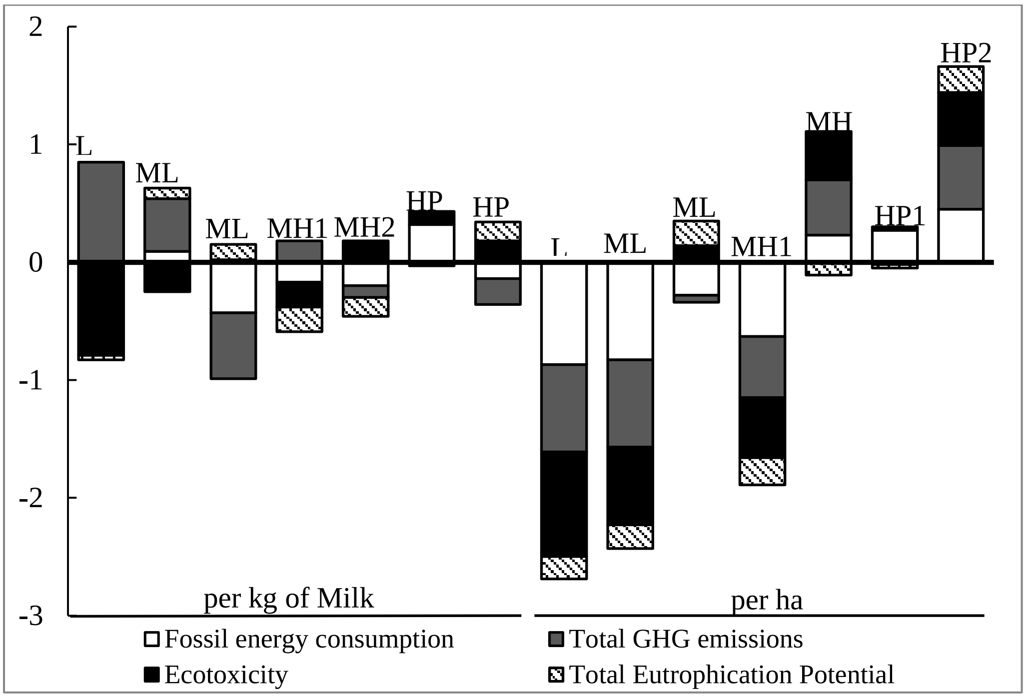

Table 3. Means for production and feed indicators, fossil energy consumption, greenhouse gas emissions, ecotoxicity, nutrient balance, eutrophication and Index of Environmental Impact (IEI) per kg of milk and per ha for the seven groups from the 277 grazing dairy production systems in Uruguay.

Variable	**Units**	**Dairy System Groups**						
		L	**ML1**	**ML2**	**MH1**	**MH2**	**H1**	**H2**
Production indicators								
Farm area	ha	44 c	122 c	82 c	243 bc	165 c	793 a	541 b
Milk productivity per ha	kg ha^{-1}	2406 d	2420 d	4702 bc	3052 d	5049 ab	4090 c	5345 a
Milk productivity per cow	kg cow^{-1}	3621 d	3485 d	5240 bc	4731 c	5725 ab	5769 a	6046 a
Stocking rate	Cow ha^{-1}	1.2 ab	1.2 ab	0.9 c	1.2 a	0.9 c	1.1 b	0.8 c
Concentrate intake per kg of milk	kg kg^{-1}	0.21 bc	0.25 ab	0.16 c	0.28 a	0.18 c	0.30 a	0.19 c
Total DM intake	kg cow^{-1}	4698 de	4345 e	5349 bc	5126 cd	5736 ab	5690 ab	5904 a
Concentrate intake per cow	kg cow^{-1}	612 e	754 de	947 cd	1024 cd	1110 c	1652 a	1401 b
Ratio MJ energy in concentrate / MJ energy in total feed		15.9 c	20.6 bc	21.5 bc	24.0 b	22.7 bc	34.5 a	27.7 ab
Environmental indicators (per kg of milk)								
Fossil energy use	MJ	3.5 ab	3.7 ab	3.0 b	3.3 b	3.3 b	4.0 a	3.4 b
Methane emissions	kg^{-1} $EqCO_2$	0.9 a	0.8 b	0.6 cd	0.7 c	0.6 d	0.6 cd	0.6 d
Nitrous oxide emissions	kg^{-1} $EqCO_2$	0.4	0.5	0.4	0.5	0.5	0.5	0.5
Total GHG emissions	kg^{-1} $EqCO_2$	1.4 a	1.3 ab	1.0 d	1.2 bc	1.1 cd	1.1 c	1.1 cd
Total Ecotoxicity	CTUe $x10^{-3}$	0.5 b	1.0 ab	1.4 a	0.9 ab	1.5 a	1.4 a	1.4 a
AEP N	PO_{4eq} $x10^{-3}$	0.8	0.8	10.0	0.5	0.6	3.4	10.0
AEP P	PO_{4eq} $x10^{-3}$	10.0 a	4.7 ab	4.4 abc	2.8 d	3.6 bcd	3.4 cd	3.8 bcd
AEP Total	PO_{4eq} $x10^{-3}$	10.8	5.5	14.4	3.3	4.2	6.8	13.8

Index of Environmental Impact		0.0	0.2	-0.8	-0.4	-0.3	0.4	-0.0
Environmental indicators (per ha)								
Fossil energy use	GJ	8.0 c	8.3 c	12.4 b	9.8 bc	16.1 a	16.4 a	17.7 a
Methane emissions	Mg CO_2-eq	2.0 c	1.8 c	2.7 ab	1.9 c	2.9 a	2.4 b	3.0 a
Nitrous oxide emissions	Mg CO_2-eq	1.0 c	1.2 c	1.7 bc	1.5 bc	2.6 a	2.0 ab	2.5 a
Total GHG emissions	Mg CO_2-eq	3.0 d	3.0 d	4.4 bc	3.5 cd	5.5 a	4.5 b	5.6 a
Total Ecotoxicity	CTUe	1.2 c	2.3 c	6.0 ab	3.0 c	7.3 ab	5.5 b	7.5 a
AEP N	PO_{4eq}	1.6	1.8	31.8	1.4	3.0	14.5	30.9
AEP P	PO_{4eq}	12.5 bcd	10.8 cd	18.6 ab	8.5 d	18.0 ab	13.9 bc	20.1 a
AEP Total	PO_{4eq}	14.2	12.6	50.4	10.0	21.0	28.4	51.0
Index of Environmental Impact		-2.7 c	-2.4 c	0.0 b	-1.9 c	1.0 ab	0.3 b	1.7 a
Index of Environmental Impact on water		-1.1 c	-0.9 c	0.4 ab	-0.7 c	0.3 ab	-0.0 b	0.7 a

The average methane emission from all the farms was 91.5 kg CH_4 Cow^{-1} $year^{-1}$ and 22.7 g CH_4 kg^{-1} milk; the N2O emission values were 3.25 kg N_2O ha^{-1} $year^{-1}$ and 1.22 g N_2O kg^{-1} milk, and total greenhouse gas emissions were 0.97 CO_2-eq kg^{-1} milk. The average contribution of each gas to total emissions was 56 % of methane, 42 % of N_2O and 2 % of CO_2. The highest emission of methane per kg of milk came from the low production group (L). No differences were detected for N_2O emissions per kg of milk between groups. However, the higher production groups (MH2, H1, H2) had the highest emissions of greenhouse gases (CH_4 and N_2O) per ha (Table 3, Figure 2). Emissions per kg and per ha increased with productivity per ha (R^2=0.73 and R^2=0.95 respectively).

Among the herbicides used for crop production in Uruguay, the higher doses correspond to glyphosate (between 71 and 90 %) for all crops. Picloram, atrazine, and acetochlor were also used for corn, sorghum, and summer annual forage crops. Total ecotoxicity per kg of milk and per hectare were highest for the groups MH2, H1, H2, and ML2 and lowest for L (Table 3, Figure 2). Ecotoxicity per kg and per ha increased with increased productivity per ha (R2=0.77 for ecotoxicity per kg and R^2=0.98 for ecotoxicity per ha). The use of perennial forages and sorghum contributed 49 % and 24 % respectively of the total ecotoxicity per ha on average (Supplemental Figure S1).

The N and P contributions by the fertilizers used for crops produced on the farm and purchased were mostly due to perennial forages and annual forage crops (Supplemental Figure S2A). The aquatic eutrophication potential per kg of milk and hectare differed only for P, but not for N (Table 3). Farm dairy effluents contributed the majority of the AEP in all groups (Supplemental Figure S2B). The aquatic eutrophication potential per kg of milk was not significantly different among groups (Table 3, Figure 2), but the AEP per ha increased with increased productivity (R^2=0.61).

The IEI per kg was not different among groups, while both IEI per hectare (the one including all impacts and the one with only water impacts) were different among groups (Table 3, Figure 2). There was no association between index of environmental impact per kg of milk and productivity per ha (p= 0.66, Figure 3) or per cow (p=0.86). There was a positive linear association between index of environmental impact in water per ha and productivity per ha ($p<0.01$, IEI= 0.0006 x Prod -2.32, R^2= 0.97, Figure 3) and per cow ($p<0.01$, IEI= 0.0006 x Prod -3.16, R^2= 0.82). A similar relationship was found for the IEI per ha including all impacts (R^2= 0.96 for productivity per ha and R^2= 0.90 for productivity per cow).

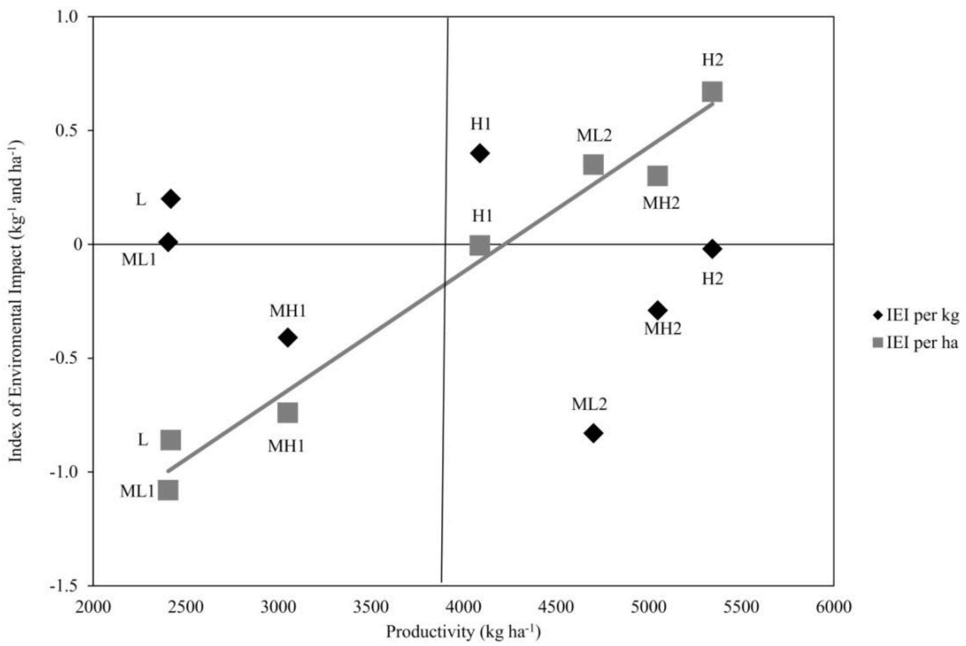

Figure 3. Index of Environmental Impact (kg milk) and Index of Environmental Impact in water (ha^{-1}) vs milk productivity (kg ha^{-1}) for seven production groups of 277 grazing dairy farms in Uruguay. Linear regression line of IEIw (ha^{-1}) is shown. Equation is given in text.

4.5. DISCUSSION

4.5.1. Fossil energy use

The fossil energy use per kg of milk results are within the same range to those reported by a range of previous studies (Thomassen et al. 2008 and O'Brien et al. 2012 in pastoral vs confined systems, and Pagani et al. 2016 and Llanos et al. 2018 in pasture-based systems). It was expected that dairy grazing systems that used greater amount of concentrates to feed their animals would use more fossil energy per kg of milk (Llanos et al. 2018). This was the case H1 group, which had the highest fossil energy use per kg of milk and the highest concentrate intake (Table 3). Consistently, ML2 had the lowest energy use per kg of milk and the lowest concentrate intake. The fossil energy use per ha was higher for high productivity farms, regardless of the concentrate intake (Table 3).

4.5.2. Greenhouse gas emissions

The variation in the GHG emissions presented here are similar to those reported in previous LCA studies developed for dairy grazing systems (Table 4). Although the IPCC, since 2006, has provided guidelines to standardize the calculation of greenhouse gases, variations in methods to quantify production, setting system boundaries, functional unit and co-product allocation, affect significantly the results, which suggests caution when different studies are compared. For example, despite the IPCC emission factor is 1.25%, the direct N_2O emissions reported from N fertilizers applied to pastures varies between zones: 0.4% in Australia (Christie et al. 2012), 1.0% in New Zealand, Ireland and Uruguay (Flysjö et al. 2011; Ledgard et al. 2019; O'Brien et al. 2012; Lizarralde et al. 2014). Similarly respect to the direct N_2O emission factors for deposition of urine and faeces on pastures which is 0.4 and 0.5% according to Christie et al. (2012), 1 and 0.25% to Ledgard et al. (2019), and 2.0% to the IPCC also used by some other researchers like Flysjö et al. (2011), O'Brien et al. (2012) and Lizarralde et al. (2014).

Our results suggest that systems with higher productivity per ha or per cow have lower greenhouse gas emissions per kg of milk. Consistently, Bargo et al. (2003) and Gerber et al. (2013) identified improvements in feeding practices and herd health management practices as important mitigation options to reduce methane emission per kg of milk, observing that the increase in the level of concentrate in the animal diet improves milk production. In addition, Johnson and Johnson (1995) had established that increasing the proportion of concentrate in the diet reduces the proportion of dietary energy converted into CH_4 and reduces the enteric CH_4 emissions per unit of milk production (Lovett et al. 2006). However, the estimation of GHG emissions per ha tells a different story: as the milk productivity per ha increases, the greenhouse gas emissions per ha also increase.

Table 4. A comparison of a set of studies of greenhouse gas emissions from dairy production systems

Approach used and methodology	**Boundaries**	**System**	**Milk productivity kg ha^{-1}**	**Milk productivity cow^{-1}**	**DMI**	**% forage in DMI**	**kg $CO_{2\text{-}eq}$ kg^{-1} milk**	**tt $CO_{2\text{-}eq}$ ha^{-1}**	**Reference**
Single year, whole farm, system model, based on typical Uruguay milk production systems	Direct on farm, purchased inputs and indirect nitrous oxide emissions	Low milk yield	2.502 kg FPCM	4.285 kg FPCM	11.0 kg/cow/d	76.4	1.09	-	Lizarralde et al. 2014
		Medium milk yield	4.198 kg FPCM	5.821 kg FPCM	13.3 kg/cow/d	52.6	0.96	-	
		High milk yield	5.377 kg FPCM	6.788 kg FPCM	15.2 kg/cow/d	38.8	0.92	-	
LCA of national statistic for New Zealand dairy farming systems	Direct on farm, purchased inputs, direct and indirect nitrous oxide emissions	Pasture grazing system	-	4.118 kg ECM	12.9 kg/ECM	92.0	1.00	-	Flysjö et al. 2011
LCA of seasonal pasture-based dairy farm from Ireland, single year, models	Direct on farm, purchased inputs, direct and indirect nitrous oxide emissions	Grass-based dairy system	-	6.639 kg/FPCM	15.1 kg/cow/d	74.0	0.87	1.20	O'Brien et al. 2012
Single year, whole farm, using methodologies, algorithms and emission factors, based stratified-random process on Australian dairy farm.	Direct on farm, purchased inputs, direct and indirect nitrous oxide emissions	Contrasting dairy farms	7.620 kg FPCM	6.270 kg FPCM	17.8 kg/cow/d	77.0	1.04	7.74	Christie et al. 2012
LCA of large survey of farms across New Zealand; system boundaries covered the trend over time of the cradle-to-farm-gate	Direct on farm, purchased inputs, direct and indirect nitrous oxide emissions	survey of farms across New Zealand	13917 kg FPCM	4.870 kg/FPCM	12.7 kg/cow/d	79.8	0.78	-	Ledgard et al. 2019

Therefore, the relationship between GHG emissions and milk productivity depends on the metrics used: from the point of view of global consumers (GHG per kg of milk) or from the perspective of the producers (GHG per ha of land). This was also reported by Becoña et al. (2014) and Picasso et al. (2014) in carbon footprint of grazing beef systems.

4.5.3. Ecotoxicity

Pesticide ecotoxicological impact depends on the dose used, soil type, rainfall, time of application, pesticide properties, residence time, and susceptibility of organisms (FAO 2013, Miguez 2017). Corn, sorghum, and the perennial forages contributed the most to the total ecotoxicity effect due to the high use of these grains in dairy farms and the herbicides involved, composed by highly toxic active ingredients such as: picloram, atrazine, and acetochlor. These are characterized for having high persistence in soil, high water solubility, low absorption, and high leaching potential reaching the groundwater aquifers, and present biological high toxic effects, from algae to most of the aquatic organisms even mammalian (FAO 2015; Grossi Botelho et al. 2011). Although some herbicides used in soybeans (e.g., haloxyfop-p-methyl) have high ecotoxic effect in water biota (Tunde Olayinka and Ore 2015), these dairy farms used little amount of soybean so this crop did not contribute much to the total ecotoxicity effect (Supplemental Figure 1).

On the other hand, crops grown in Europe have often lower ecotoxicity effect than those grown in North and South America, due to the fact that most toxic pesticides are banned in Europe (Nordborg, 2013). The ecotoxicity impact both per kg of milk and ha, was higher for more productive farms, which could be due to a combination of the more productive farms using more concentrates and more area under crops. Intensification approaches which rely on pesticides to increase crop yields have also degraded water quality threatening human and wildlife health (Relyea 2005). Diversifying crop rotations is a way to control weeds while simultaneously enhancing other desirable agroecosystem processes; increasing the use of the pastures in the animal diets is another way to reduce ecotoxicity (Davis et al. 2012).

4.5.4. Eutrophication potential

Nutrient losses, particularly N and P, have a number of environmental consequences either in the atmosphere as in the quality of soils and water (Schröder et al. 2004). Dairy farms N and P losses come mostly from the use of fertilizers, dairy effluents and the generation of large amounts of manure, causing environmental problems (Longhurst et al. 2000; Xue 2011), especially aquatic eutrophication as has been documented in watersheds of Uruguay (Pacheco et al. 2012). The excess of nutrients grows as the milk production and purchased feed increase (Herrero et al. 2006; Thomassen 2008; García et al. 2007), although the data observations pop up from this work was not that linear. This has been documented given the lower prices of the fertilizers and concentrates in the last decade, compared to the cost of land and labour, and therefore, dairy farms tend to rely on large inputs of nutrients in fertilizers to enable high crop production. Furthermore, inputs of feed concentrate increased because of an increased number of cows per hectare and the need to improve the quality in the diet of high yielding cows (Fangueiro et al. 2008). The use of concentrate is a strategic resource to provide feed during the period of the year when the forage supply may be scarce, and therefore, to ensure the best conditions for their production (Krüger et al. 2014). Nevertheless, systems with proper handling of pasture consumption can achieve elevated productive values and lower eutrophication effects (Satter et al. 2005; Houlbrooke 2008), as it was observed on the MH2 group. Adequate management strategies that effectively reduce the amounts of nutrients from dairy farms can decrease nutrient losses to waterways (Christensen et al. 2012; McDowell et al. 2013). In fact, according to Nash et al. (2019) good management practice at applied fertilizers, make a minor (e.g., <10%)

contribution to total P exports, and therefore it would be possible to decrease the stream of P into the water (McDowell et al. 2019).

4.5.5. Integrated indices of environmental impact

Our first hypothesis was rejected: groups of dairy systems with higher milk production did not have lower integrated global environmental impact per kg of milk than systems with lower milk production (Figure 3). Although greenhouse gas emissions per kg indeed were reduced with increased milk productivity (Table 2), the other impacts remain the same (fossil energy use and eutrophication potential per kg) or increased (ecotoxicity per kg). Our second hypothesis was not rejected: groups of dairy systems with higher milk production had higher local environmental impact per ha of land than systems with lower milk production (Figure 3). This was the case for all individual impacts per unit of ha, and for the integrated indices also. These results show that increasing milk productivity per se does not imply reduction on global environmental impacts, and certainly increased local environmental impacts. The management practices used for increasing productivity have a critical role in the environmental impacts.

Dairy systems intensification trajectories imply increase in productivity which requires increase in dry matter intake (Table 3); when the increase in intake is based on higher pasture consumption, and less concentrate per kg of milk, global environmental impacts (fossil energy use and GHG) per kg of milk can be reduced. This was the case for instance for ML1 vs ML2, and H1 vs H2. However, the local environmental impacts per ha increase when productivity increases, due to a greater overall feed consumption, increase of dairy effluents and greater use of agrochemicals to produce the feed. Previous studies have focused on reporting global environmental impacts from the standpoint of the consumer, and therefore expressed per kg of milk. Environmental impacts should also be expressed per unit of land area (ha) to account for the total contribution of a farm without the dilution effect of the productivity (Dijkstra et al 2013). For instance, the goal should be to minimize the total contribution of greenhouse gas emissions to climate change, not just the emission intensity. This is particularly relevant for direct impacts at the local level, like ecotoxicity and aquatic eutrophication.

The ability of ecosystems to absorb pollution (nutrients of toxic substances) depends on the area of that ecosystem. Therefore, for critical environmental issues at the local level, like improving water quality, impacts on water should be reported per ha (Repar et al. 2016, Flaten et al. 2018, Picasso et al. 2014). Although composite indices of environmental impacts have limitations, and should only be used to complement the individual environmental impact variables, our results show that when integrating all impacts no differences are found per kg of milk, but overall impacts per ha increase with productivity.

One limitation of this work was the lack of data to evaluate the quality of the pasture and feed, to provide better estimations of greenhouse gases and nutrient excess. The index of environmental impacts proposed did not include soil erosion, which is a very relevant component of farm sustainability. Also, different methods of weighing the global and local indicators were not evaluated, which may affect the results for the global impacts. Furthermore, future research should include economic and social indicators to provide a more holistic assessment of sustainability of dairy systems.

4.6. CONCLUSIONS

The evaluation of a range of individual environmental indicators and integrated indices of environmental impact allowed to integrate multiple environmental variables and assess the trade-offs between different global and local impacts. Contrasting results were obtained when assessing impacts per kg of milk and per hectare. Dairy systems with higher milk production had lower greenhouse gas emissions but higher ecotoxicity per kg of milk than systems with lower milk production, and the integrated index did not change.

On the other hand, all the studied indicators per hectare of land: fossil energy use, greenhouse gas emissions, eutrophication, ecotoxicity, and the integrated indices presented higher values for the higher milk production systems. The results suggest that increasing milk productivity is not necessarily associated with reduced environmental impacts per kg, and increased impacts per ha. The combination of management factors including type of diet (pasture vs concentrate), amount of inputs, and type of grazing system may be more relevant in determining environmental impacts of dairy systems than productivity per se, and should be the focus of further research.

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4.9. SUPPLEMENTAL

Supplemental Table S1. Energy coefficients and the used criteria to calculate fossil energy (Agroenergía model - Llanos et al. 2013)

Input (unit)	Energy (MJ/unit)	Criteria	Reference
Diesel (l)	39	Calorific value of diesel used in Uruguay, analyzed by bomb calorimeter.	Ministerio de Industria Energía y Minería (2017)
Herbicides (kg)	267	Include the formulation of the active compounds in oils, powders or granules, packaging and transport	West and Marland (2002)
Urea (kg)	54	IFA simplified model uses natural gas as a Source of ammonia production (80% of world production)	Kongshaug (1998)
Diammonium phosphate (18-46-0)	45		
Mixture II (0-40/41-0+3s)	7.0		
Super concentrated nitrogenous (7-40+5)	45		
Superphosphate (0-20/22-0-12s)	3.2		
Milk (kg)	3.05	Based on the percentages of fat (3.72 %F) and milk protein (3.37 %P) for all farm (DIEA 2014)	Llanos et al. (2013)
Cattle Category:		The energy value from the weight of the different tissues	Llanos et al. (2013)
Milking Cow 530 Kg	7959		
Breeding stock 260 Kg	3575		
Heifer 400 Kg	5753		
Steer 350 Kg	4601		
Calf 35 Kg	255		
Bull 600 Kg	7507		

Supplemental Table S2. Description and IPCC (2006a) equations of the different livestock categories used for calculating methane emissions

Description	Equation	Unit	Bulls	Milking cows	Heifers	Cattle growing	Calves	Calf
Body Weigh	Data	kg $head^{-1}$	600	530	400	260	350	35
Weight daily gain	Data	kg d^{-1}	-	-	-	0.45	0.60	0.45
Digestibility	Table 10.2	%	55	55	55	55	75	75
Coefficients of net energy for maintenance	Table 10.4	Mj d^{-1} kg^{-1}	0.37	0.38	0.32	0.32	0.32	0.32
Net energy for maintenance	Equation 10.3	Mj d^{-1}	44.9	42.6	28.8	20.8	26.1	4.60
Net energy for activity	Equation 10.4	Mj d^{-1}	7.63	7.25	4.90	3.54	4.43	-
Net energy for growth	Equation 10.6	Mj d^{-1}	-	-	-	6.35	10.9	1.41
Net energy for lactation	Equation 10.8	Mj d^{-1}	-	43.1*	-	-	-	-
Net energy for pregnancy	Equation 10.13	Mj d^{-1}	-	4.26	2.88	-	-	-
Gross energy	Equation 10.16	Mj d^{-1}	203	207*	141	142	116	16
CH_4 emission for enteric fermentation	Equation 10.21	kg CH_4 $head^{-1}$ yr^{-1}	86.5	88.4*	60.3	60.7	49.6	7.10

* Average values calculated from each of the dairy farms, using the gross energy calculated from the CIPIL model (Astigarraga 2004)

Supplemental Table S3. Dry matter percentage (DM) of the crops, N and P present in the produced grain

	Corn Lex	Wheat bran	Soy Peel	Soy Expeller	Alfalfa hay mature	Perennial grasses	Corn grain	Seeded pastures	Sorghum grain	Winter annual forage crops	Summer annual forage crops
% DM	88	87.4	89	91	88	88	88	90	89	89	88
% N	2.5	2.4	1.7	7.98	2.08	2.4	1.44	1.6	1.76	2.4	1.44
% P	0.82	1.38	0.17	0.68	0.19	0.25	0.3	0.3	0.32	0.48	0.22

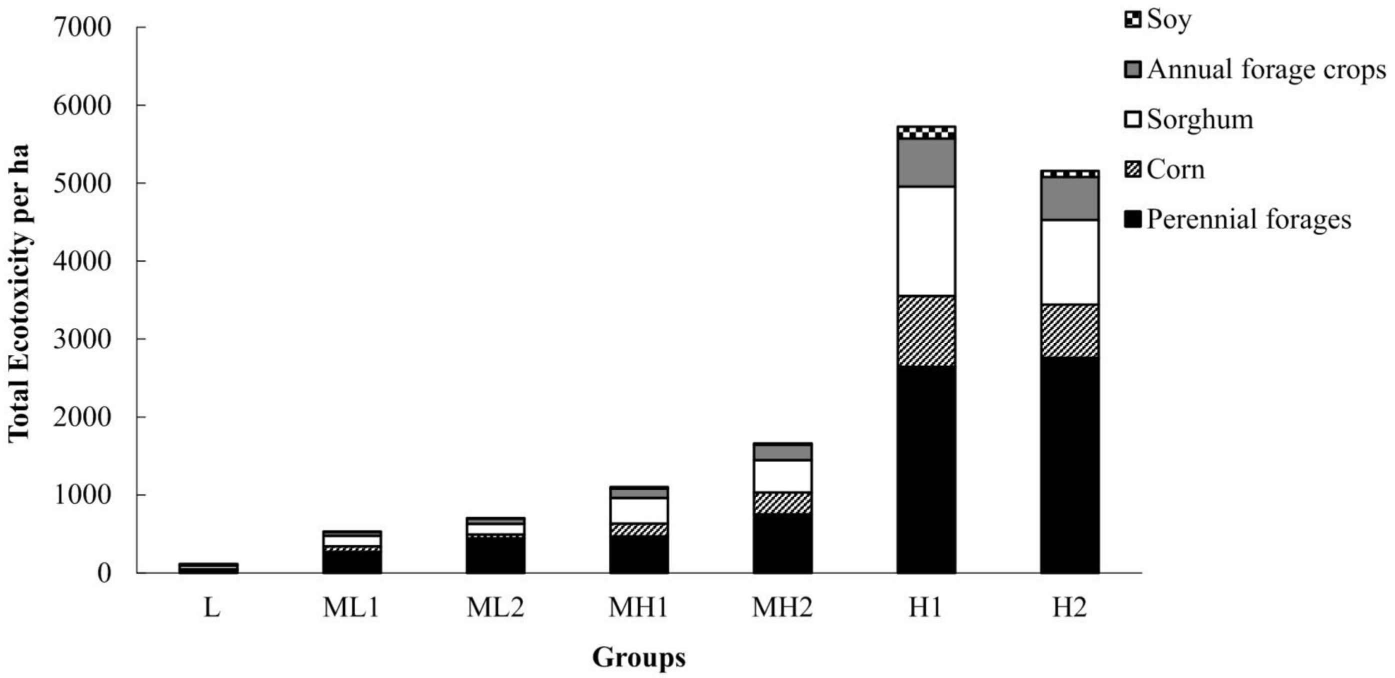
Source: Fernández Mayer 2014

Supplemental Table S4. Standard deviation (SD), variation coefficient (VC) of the production, energy, greenhouse gas emissions ecotoxicity, eutrophication, and index of environmental impact of the seven groups from the 277 grazing dairy production systems in Uruguay in 2014.

Variable	**Units**	**Groups**													
		L		**ML1**		**ML2**		**MH1**		**MH2**		**H1**		**H2**	
		SD	**VC**	**SD**	**VC**	**SD**	**VC**	**SD**	**VC**	**SD**	**VC**	**SD**	**VC**	**SD**	**VC**
Production indicators															
Farm area	ha	23.7	53.1	47.5	38.7	42.5	51.8	85.5	35.1	62.8	37.9	665	83.8	373	68.9
Milk productivity per ha	kg ha^{-1}	933	38.8	659	27.2	1806	38.4	719	23.6	1593	31.6	1392	34.1	1566	29.3
Milk productivity per cow	kg cow^{-1}	1578	43.6	712	20.4	1339	25.6	1175	24.8	872	15.2	1073	18.6	1237	20.5
Stocking rate	Cow ha^{-1}	0.32	27.4	0.32	27.0	0.15	17.1	0.37	30.2	0.21	22.3	0.29	26.8	0.18	22.0
Herd efficiency	Milking cows $stock^{-1}$	0.10	13.6	0.16	23.5	0.14	18.4	0.12	16.2	0.12	14.8	0.09	11.2	0.11	13.4
Concentrate intake per kg of milk	kg kg^{-1}	0.11	54.6	0.15	60.1	0.07	41.8	0.15	54.6	0.10	58.3	0.10	33.2	0.07	39.5
Total dry matter intake	kg cow^{-1}	1117	23.8	524	12.1	916	17.1	753	14.7	625	10.9	717	12.6	804	13.6
Concentrate intake per cow	kg cow^{-1}	382	62.4	379	50.3	432	45.6	461	45.0	650	58.6	585	35.4	600	42.8
Ratio MJ energy in concentrate / MJ energy in total feed		8.58	53.8	9.80	47.5	9.03	42.1	10.0	41.6	11.8	52.2	10.0	29.0	10.0	36.1
Percent of intake from pasture		12.9	18.4	14.6	22.9	15.6	26.2	15	26.3	17.2	30.0	10.7	26.8	11.2	20.0
Percent of intake from silage		10.1	61.8	11.9	62.7	12.4	54.2	12.1	52.8	14.0	58.7	8.94	28.6	9.29	45.5
Percent of intake from concentrate		7.09	52.9	8.36	48.3	7.62	43.0	8.42	42.1	10.1	53.8	8.87	30.8	8.92	38.2
Environmental indicators (per kg of milk)															
Fossil energy consumption	MJ	1.82	51.4	1.76	47.4	2.04	69.3	1.58	47.6	1.54	46.8	1.09	27.0	1.16	34.5
Methane emissions	kg^{-1} $EqCO_2$	0.28	30.2	0.17	22.2	0.09	16.1	0.14	22.1	0.1	17.1	0.09	14.6	0.08	13.9

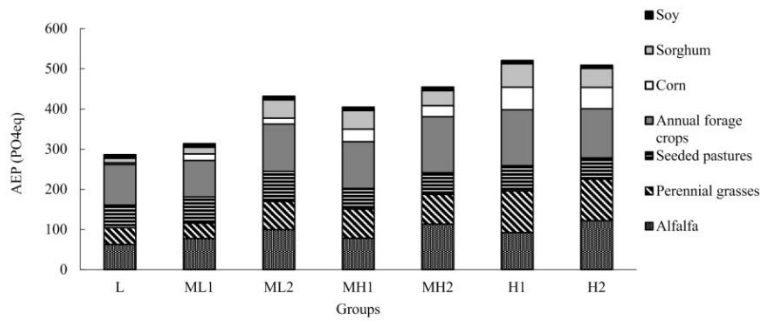
Nitrous oxide emissions	kg^{-1} EqCO_2	0.24	54.4	0.3	60.5	0.2	54.7	0.29	56.2	0.25	51.2	0.22	46.4	0.18	38.9
Total GHG emissions	kg^{-1} EqCO_2	0.42	30.7	0.27	21.3	0.24	24.8	0.35	30.2	0.27	24.7	0.27	24.1	0.21	19.8
Total Ecotoxicity	CTUe	0.00076	168.7	0.0011	111.3	0.0012	87.9	0.0011	113.2	0.001	67.9	0.00098	69.5	0.0011	76.1
Excess N	kg	0.0019	174.7	0.00066	15248.2	0.00053	265.4	0.00072	248.6	0.00036	169.2	0.00032	138.1	0.00026	105.7
Excess P	kg	0.0007	117.4	0.00027	187.8	0.00019	79.6	0.00024	845.9	0.00013	420.4	0.00011	368.4	0.000073	182.6
AEP N	PO_{4eq}	0.00072	91.9	0.00046	59.9	0.021	422.6	0.00049	104.4	0.00044	73.1	0.019	559.4	0.026	433.1
AEP P	PO_{4eq}	0.0044	80.7	0.0027	58.6	0.0024	55.4	0.0027	96.5	0.0026	73.7	0.0019	56.4	0.0027	70.3
AEP Total	PO_{4eq}	0.0051	81.6	0.0032	59	0.021	219.4	0.0032	98.2	0.0031	73.7	0.019	275.6	0.026	259.6
Index of Enviromental Impact		2.88	423	2.26	561	3.06	414	3.02	1322	2.49	1100	1.94	754	1.87	450
Environmental indicators (per ha)															
Fossil energy consumption	MJ	5114	63.3	3327	40.1	5917	47.8	4500	45.8	7918	49.2	6769	41.2	7428	41.9
Methane emissions	tt^{-1} of CO_2-eq	0.6	29.9	0.52	29.4	0.9	33.5	0.48	24.9	0.99	34.2	0.68	28.1	0.88	28.9
Nitrous oxide emissions	tt^{-1} of CO_2-eq	0.61	61.6	0.9	73.1	1.13	66.8	0.84	55.5	1.58	62.1	1.33	65.7	1.46	57.4
Total GHG emissions	tt^{-1} of CO_2-eq	1.03	33.8	1.07	35.5	1.84	41.8	1.1	31.6	2.31	41.9	1.85	41.1	2.19	38.8
Total Ecotoxicity	CTUe	2	160.3	2.1	89.5	5.1	84.4	2.9	94.6	4.9	67.3	3.8	69	5.4	72.8
Excess N	kg	5	183.9	1.5	16696.9	2.4	231.5	2.2	261.5	1.7	154.9	1.4	148.8	1.3	101.2
Excess P	kg	1.8	111.8	0.6	206.6	1.1	89.1	0.8	887.4	0.6	359	0.5	437	0.4	206.6
AEP N	PO_{4eq}	1.3	81.7	1.2	66.3	141.7	445.5	1.4	97.7	3.1	101.6	87.3	600.7	131.2	425.2
AEP P	PO_{4eq}	9.7	77.8	7.2	66.7	11	59.3	7.6	89.6	18.1	100.6	9.5	68.8	15.6	77.7
AEP Total	PO_{4eq}	11	77.8	8.4	66.5	138.8	275.4	9	90.5	21.1	100.7	85.8	302.3	127.9	251
Index of Environmental Impact		1.69	72.4	1.43	60.8	2.83	7631	1.59	86.8	3.7	218	2.38	1551	2.93	209

Supplemental Figure S1. Potential freshwater ecotoxicity impact of the herbicides per ha, of each crop and forage per production system group.

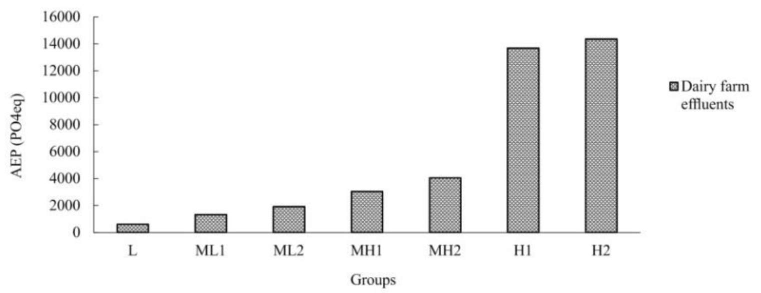


Supplemental Figure S2. Eutrophication potential per ha of each crop per production system group. A. Crops and forages. B. Dairy farm effluents.

A



B



5. DISCUSIÓN GENERAL

La investigación científica asociada a los impactos ambientales que se generan en los sistemas de producción ha incrementado en los últimos años, en especial América Latina (Rodríguez, et al. 2015), estos estudios analizan el tema desde diferentes perspectivas y metodologías. A pesar de las diferentes recomendaciones y reportes asociados a los impactos ambientales, la rentabilidad de los sistemas productivos bajo presiones del mercado obliga a los productores a mejorar la productividad mediante una mayor utilización de insumos (por ejemplo, fertilizantes, suplementos), y al mismo tiempo exige reducir los costos de producción, aunque estas medidas finalmente no siempre se reflejan en el aumento del retorno económico.

En la actualidad el se han generados debates de la sustentabilidad entre los sistemas de producción a pastoreo y los sistemas intensivos. Los defensores de la producción a pastoreo son muy críticos por el consumo intensivo de alimentos para el ganado al competir con granos que la gente podría comer directamente, en un contexto de seguridad alimentaria e incremento de la población mundial (Garnett et al 2017). La ganadería de base pastoril permite el consumo de materiales fibrosos y otras fuentes de alimento que los humanos no pueden comer directamente, y convertirlos en fuentes proteicas para el consumo humano.

En la exploración de investigaciones sobre la intensificación de los sistemas de producción lecheros, la eficiencia económica y los impactos ambientales a nivel internacional, se han evaluado diferentes estrategias a partir de datos prediales representativos de la lechería comercial, que han permitido dentro del contexto de este debate aportar conocimientos necesarios para la región, en especial Uruguay. El objetivo general de este trabajo fue analizar los efectos económicos, ambientales, productivos segun diferentes estrategias de producción basadas en la proporción de pasturas y de alimentos concentrados utilizados en el sistema productivo.

En los capítulos 3 y 4 de este trabajo de tesis, se ha analizado los impactos ambientales según diferentes estrategias de alimentación del rodeo lechero a nivel nacional. Esta última sección del trabajo enumeramos los principales aspectos que merecen una mayor discusión en función de las hipótesis planteadas en la tesis.

5.1. ¿SE PUEDEN IDENTIFICAR SISTEMAS INTENSIVOS ECONOMICAMENTE VIABLES CON UNA ESTRATEGIA DE ALIMENTACION FUNDAMENTALMENTE PASTORIL?

En el capítulo 3 de esta tesis señalamos que la intensificación de los sistemas de producción de leche asociados con el uso de concentrados y reservas, ha aumentado la productividad con efectos variables sobre el costo económico. En este sentido hay algunas consideraciones que merecen ser analizadas como por ejemplo la eficiencia económica y los costos de producción.

La eficiencia económica se mide utilizando los datos de precios de salida sobre las entradas. La eficiencia de un predio lechero tiene como objetivo maximizar los ingresos (venta de leche, carne, otros) y minimizar los egresos (compra de insumos, mantenimiento, impuestos y mano de obra). Es por ello que cuando se habla de buscar la eficiencia económica, se habla de reducción de costos o aumento de margen bruto.

Si bien hay elementos propios que se pueden mejorar dentro de cada predio como la reproducción, y las prácticas de manejo que conllevan a mejorar los aspectos financieros a largo plazo, los cambios en la alimentación pueden observarse fácilmente a corto plazo. Algunos estudios han encontrado un impacto negativo en la compra de alimentos que ingresan al predio que afecta el desempeño económico del predio (Kauffman y Tauer 1986; Schorr y Lips 2018). Es por ello que el alimento es un gasto importante para cualquier predio lechero, pudiendo representar hasta el 80 % del costo de producción (DIEA 2019b), por lo que tener eficiencia en el uso del alimento afecta la eficiencia económica, pero también lo hace el valor económico de los componentes de la leche (VandeHaar et al. 2016). Sin embargo, otros costos también son importantes, como la mano de obra, aplicación de nuevas tecnologías de alimentación y las mejoras genéticas que también deberían estar disponibles para lograr que las vacas requieran menos alimento por unidad de leche (Kauffman y Tauer 1986; VandeHaar et al. 2016).

Por otro lado Kauffman y Tauer (1986) encontraron que la producción de leche era un factor esencial en la mejora del resultado económico a nivel predial. Para los casos analizados, estos autores reportan que al aumentar la producción de leche por vaca en un 10%, el resultado economico aumentó un 3%.

Entonces, podríamos señalar, que en base a nuestros resultados, hemos identificado sistemas más intensivos que usan una mayor proporción de pastura en las dietas y tienen un uso más eficiente del alimento concentrado, con una mayor respuesta en leche a los suplementos, y tienden a mejorar su desempeño económico. Resultados similares fueron reportados por Lizarralde et al (2014) a partir de estudios de casos de predios lecheros comerciales en Uruguay, otros trabajos a nivel internacional son consistentes con estos resultados como lo son Parker et al. (1992); Dartt et al. (1999); Somda et al. (2005).

Otro aspecto a considerar es, que en nuestro caso no hubo diferencia en los ingresos netos a partir de un incremento en el contenido de la grasa y proteína en la leche en diferentes grupos (datos no mostrados), que podrían estar asociados a una mejor calidad y cantidad en el consumo del alimento concentrado. Resultados similares han sido publicados por Yayota et al. (2013), en la cual realizaron un estudio en diferentes unidades de producción lecheras con componentes alimenticios característicos de cada región: ensilado de pasturas, ensilaje de maíz, y sub-productos por ejemplo, residuos de soja o granos de destilería, en la cual, los contenidos de grasa y proteína de la leche, no mostraron diferencias entre los sistemas de alimentación. Es por ello que entender con mayor claridad los mecanismos involucrados en la formación de sustratos para la síntesis de la grasa y la proteína de la leche de vaca, así como sus interrelaciones con la nutrición, la raza, el ambiente ruminal, y la variabilidad genética del ganado, son de gran importancia para no incrementar los costos económicos del alimento concentrado esperando incrementar los ingresos económicos en la producción.

5.2. ¿QUÉ RELACIÓN EXISTE ENTRE LAS ESTRATEGIAS DE INTENSIFICACIÓN Y LOS IMPACTOS AMBIENTALES?

En este trabajo de tesis señalamos como hipótesis que la intensificación de los sistemas de producción de leche asociados con el uso de concentrados y reservas, aumenta la productividad por unidad de superficie, con efectos variables sobre el costo económico y la eficiencia energética. Nuestros resultados señalan que la intensificación de los sistemas de pastoreo requiere un uso eficiente de las pasturas y de los alimentos concentrados, de modo que la proporción de la ingesta de forraje sea alta, y la eficiencia del uso de concentrado (kg de leche / kg de concentrado) también sea alta (Lizarralde et al 2014). El incremento moderado en el uso de concentrados desde niveles muy bajos y la carga animal, simultáneamente mejorarían los ingresos netos y aún mantendrían o mejorarían la eficiencia energética. Esta estrategia puede lograr al mismo tiempo una alta productividad de leche, un alto ingreso económico neto y un bajo uso de energía fósil (Capitulo 3).

La segunda hipótesis señala que los sistemas de producción de leche con mayor producción tendrán un menor impacto ambiental global por kg de leche que los sistemas con menor producción de leche: Sin embargo, los resultados de este trabajo muestran que los sistemas lecheros con mayor producción de leche no tuvieron un menor impacto ambiental global integrado por kg de leche que los sistemas con menor producción de leche (Capitulo 4). Aunque las emisiones de gases de efecto invernadero por unidad de producto se redujeron con el aumento de la productividad de la leche, los otros impactos analizados permanecieron igual (uso de energía fósil y potencial de eutrofización por kg) o aumentaron (ecotoxicidad por kg).

La tercera hipótesis señala que los sistemas de producción de leche con mayor producción tendrán un mayor impacto ambiental local por unidad de superficie que los sistemas con menor producción de leche, lo cual fue confirmado por el análisis presentado en el Capitulo 4. Este fue el caso para todos los impactos individuales por unidad de ha, y también para los índices integrados. Los resultados muestran que el aumento de la productividad de leche no esta asociado a una reducción de los impactos ambientales globales, y ciertamente aumenta los impactos ambientales locales.

Tanto los resultados del capitulo 3 como del capitulo 4, ponen en evidencia que las estrategias de alimentación utilizadas para aumentar la productividad tienen un papel fundamental en los impactos ambientales. Las trayectorias de intensificación de los sistemas lecheros implican un aumento en la productividad que requiere un aumento en la ingesta de materia seca. Cuando el aumento en la ingesta se basa en un mayor consumo de pasturas y menor de concentrado por kg de leche, los impactos ambientales globales (uso de energía fósil y GEI) por kg de leche pueden reducirse. Sin embargo, los impactos ambientales locales por hectárea aumentan cuando aumenta la productividad, debido a un mayor consumo general de alimento, un aumento de los efluentes y un mayor uso de agroquímicos para producir el alimento.

Estudios anteriores se han centrado en reportar los impactos ambientales globales desde el punto de vista del consumidor y, por lo tanto, expresados por unidad de producto. Los impactos ambientales también deben expresarse por unidad de superficie, para tener en cuenta la contribución total de un sistema de produccón sin el efecto de dilución de la productividad (Dijkstra et al 2013). Stott y Gourley (2016) encontraron que la intensificación basada en un aumento en la producción de leche por hectárea conduce a un aumento en las pérdidas de nitrógeno al medio ambiente. Esto es particularmente relevante para los impactos directos a nivel local, como la ecotoxicidad y la eutrofización acuática. La capacidad de los ecosistemas para absorber la contaminación (nutrientes de sustancias tóxicas) depende del área de ese ecosistema (Repar et al.2016). Por lo tanto, para problemas ambientales críticos a nivel local, como la calidad del agua, los impactos deben informarse por unidad de superficie (Repar et al.2016, Flaten et al. 2018, Picasso et al.2014). Del mismo modo, Chobtang et al. (2017) también observaron que la intensificación, si se combina con una mayor eficiencia en la utilización de las pasturas, puede conducir a la sostenibilidad ambiental y a aumentar la productividad de los animales.

Identificar los vínculos entre los recursos naturales y al mismo tiempo, mejorar su eficiencia, es una estrategia que beneficiaría a las generaciones actuales y futuras al crear sostenibilidad, al tiempo que permite el aumento de la producción de alimentos (Struik et al. 2014). Sin embargo, los compromisos (trade-off) son mucho más frecuentes que las sinergias, y para tomarlos en cuenta se requiere un enfoque completamente diferente (Struik et al. 2014).

La evaluación de una gama de indicadores ambientales individuales e índices integrados de impacto ambiental permite integrar múltiples variables ambientales y evaluar los compromisos entre los diferentes impactos globales y locales. En este trabajo, se obtuvieron resultados contrastantes al evaluar los impactos por unidad de producto y por unidad de superficie . Los sistemas lecheros con mayor producción tuvieron menores emisiones de gases de efecto invernadero pero mayor ecotoxicidad por unidad de producto que los sistemas con menor producción de leche, mientras que el índice integrado no varió. Por otro lado, todos los indicadores estudiados (uso de energía fósil, emisiones de gases de efecto invernadero, eutrofización, ecotoxicidad y los índices integrados) presentaron valores más altos (siendo mas nocivos) para los sistemas de producción de leche con mayor producción por unidad de superficie.

Sin embargo, la combinación de factores de manejo que incluyen el tipo de dieta (pasto versus concentrado), la cantidad de insumos y el tipo de sistema de pastoreo puede ser más relevante para determinar los impactos ambientales de los sistemas lecheros que la productividad per se, y debería ser el foco de más investigación. La intensificación ya sea a base de pasturas o de alimentos concentrados puede generar visiones sesgadas de los impactos ambientales como señalan Van Apeldoorn et al. (2013). Según estos autores, la intensificación depende en gran medida de las características de las regiones (suelos, régimen hídrico, topografia), reconociendo interrelaciones entre la intensificación y el ecosistema que no pueden obtenerse mediante métodos lineales..

5.3. ¿CÓMO LAS DIFERENTES ESTRATEGIAS DE INTENSIFICACIÓN AFECTAN EN EL IMPACTO AMBIENTAL A NIVEL GLOBAL Y A NIVEL LOCAL?

Investigaciones anteriores han demostrado que a menudo existen compromisos entre los impactos ambientales globales (por ejemplo, uso de energía fósil y emisiones de gases de efecto invernadero) y locales (por ejemplo, ecotoxicidad y eutrofización del agua) en los sistemas ganaderos (Modernel et al. 2013, 2018). Estas dos métricas pueden proporcionar diferentes resultados (Picasso et al. 2014).

La elaboración de indicadores ambientales nos permite estimar el daño potencial al ambiente, sin embargo, varios autores señalan que los problemas ambientales de naturaleza local y global deben considerarse por separado con diferentes tipos de indicadores (Payraudeau y Van Der Werf 2005; Repar et al. 2017; Van Der Werf y Petit 2002) representando un desafío para la evaluación del desempeño ambiental. Para responder esta pregunta es necesario definir que se entiende por impacto local e impacto global.

Los impactos ambientales de relevancia global se expresan por unidad de producto, es decir por kg de leche, mientras que los impactos ambientales de relevancia local se expresan por unidad de superficie (Repar et al. 2016; Flaten et al. 2018).

Del mismo modo Payraudeau y Van Der Werf (2005) consideran los impactos locales y globales, dependiendo de la distancia entre la fuente de emisión y el área afectada por cada tipo de impacto. Si el impacto ambiental local por unidad de superficie es mayor que la capacidad de carga del ecosistema, entonces la situación no es sostenible desde el punto de vista ambiental (Repar et al. 2017). El impacto global mide según estos autores, la intensidad del impacto ambiental del predio o del sistema de producción, en toda la cadena productiva, siendo el efecto invernadero y el uso de energía no renovable los indicadores de mayor peso en los impactos globales (Payraudeau y Van Der Werf 2005) medidos en términos de producción (por unidad de litros de leche).

En el capítulo 4, señalamos como hipótesis que los sistemas de producción de leche con mayor producción tendrán un mayor impacto ambiental local por hectárea que los sistemas con menor producción de leche. Idealmente, un análisis ambiental debería considerar los efectos locales y globales, para evitar un aumento concomitante del impacto global al intentar reducir el impacto local (o viceversa), como señala Repar et al. (2016). Según estos autores, existe una correlación negativa entre estos dos indicadores, significando que cualquier mejora en el desempeño ambiental global resultará en un deterioro del desempeño ambiental local y viceversa. Este razonamiento nos genera mayores interrogantes, para conocer en qué grado la intensificación a partir del uso de pasturas se asocia a incrementar los impactos globales mientras disminuyan los impactos locales, siendo un tema para seguir investigando y generando información.

Si bien nuestros resultados muestran que los sistemas lecheros con mayor producción tuvieron menores emisiones de gases de efecto invernadero por kg de leche, los indicadores de ecotoxicidad fueron mayores que en los sistemas con menor producción de leche, y finalmente el índice integrado no varió. En cambio, todos los indicadores estudiados por hectárea (uso de energía fósil, emisiones de gases de efecto invernadero, eutrofización, ecotoxicidad y los índices integrados) presentaron valores más altos para los sistemas de producción de leche con valores mas altos de productividad. Estos resultados sugieren que el aumento de la productividad de la leche no está necesariamente asociado con menores impactos ambientales por unidad de producto pero sí mayores impactos por unidad de superficie según la estrategia actual basada en mayor uso de insumos. La combinación de estrategias de intensificación que incluyen mayor proporción de pasturas en los sistemas productivos a la vez que dismunyan el uso de agroquímicos por unidad de superficie, puede ser más relevante para determinar los impactos ambientales de los sistemas lecheros que la productividad per se, y debería ser el foco de más investigación, para determinar si es posible reducir los impactos locales sin incrementar los impactos globales y visceversa.

6. CONCLUSIONES Y RECOMENDACIONES

La evaluación de una gama de indicadores ambientales individuales e índices integrados de impacto ambiental permitió integrar múltiples variables ambientales y evaluar las compensaciones entre los diferentes impactos globales y locales. Se obtuvieron resultados contrastantes al evaluar los impactos por unidad de producto y por unidad de superficie.

Los sistemas lecheros con mayor producción de leche presentaron menores emisiones de gases de efecto invernadero pero mayor ecotoxicidad por unidad de producto que los sistemas con menor producción de leche, mientras que el Indice Estandarizado Integrado de impactos ambientales (IEI) no varió. Por otro lado, todos los indicadores estudiados por unidad de superficie (uso de energía fósil, emisiones de gases de efecto invernadero, eutrofización, ecotoxicidad y IEI) presentaron valores más altos (más nocivos)para los sistemas de producción de leche con mayor productividad.

Los resultados sugieren que el aumento de la productividad de la leche no está necesariamente asociado con impactos ambientales menores por unidad de producto pero sugieren mayores impactos ambientales por unidad de superficie. La combinación de factores de manejo como el tipo de estrategia de alimentación del rodeo lechero (proporción de pasturas y de alimentos concentrados) y la cantidad de agroquimicos, puede ser más relevante para determinar los impactos ambientales de los sistemas lecheros que la productividad per se, lo cual podría ser el foco a futuro de la investigación para diseñar sistemas de producción más sustentables desde el punto de vista ambiental y viables desde el punto de vista económico y aceptable desde el punto de visto social.

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