Marginal Abatement Cost Curves for Latin American Dairy Production: A Costa Rica case study

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Abstract:	This study utilises data collected from Costa Rican dairy farmers to conduct a cradle to farm gate Life Cycle Assessment and the first Marginal Abatement Cost Curve (MACC) for dairy production in Latin America. Ninety dairy farms across five farm typologies were assessed, reflecting Costa Rica's diverse agroclimatic zones and varying degrees of dairy/beef specialisation. The efficacy and cost-effectiveness of specific mitigation measures depend on farm typology, but several promising technologies are identified that increase efficiency whilst substantially reducing emissions across most farms – in particular, measures that improve animal health and increase pasture quality. Pasture measures are synergistic with silvopastoral practises and are highly effective at emission mitigation, although relatively expensive. The replacement of lower quality by-product feeds with high quality concentrate feed is a cost-effective mitigation measure at farm level, but emission reductions could be negated by indirect land use change outside the scope of the MACC analyses. Achieving carbon neutrality at farm level is not likely to be possible for most farms, with the exception of extensive farm typologies. Not all measures are suitable in every context, and additional policy support will be needed to offset financial and technical challenges related to adoption. Results of this first tropical dairy MACC study are constrained by lack of high-resolution data, but they highlight the need for farm-typology-specific mitigation recommendations. Overall, there is a high potential for pasture improvement and silvopastoral measures to mitigate the globally significant contribution of Latin American livestock production to climate change.

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25/09/2020

Paper Submission to the Journal of Cleaner Production

Dear Members of the Editorial Team

We wish to submit our article entitled, “*Marginal Abatement Cost Curves for Latin American Dairy Production: A Costa Rican case study*” for review by journal of Cleaner Production.

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

In this manuscript we utilise life cycle analysis data on Costa Rican Dairy farms in conjunction with data gathered from literary sources and consultation with in-situ experts to produce the first Marginal Abatement Cost Cure (MACC) in a Latin America and Caribbean (LAC) context. In addition to the MACC analysis, the paper also presents a feasibility study that assess the fit of each of the assessed environmental measures to each of the included dairy farm typologies. This work compliments well a recent piece, also based around this project and published in the Journal of Cleaner Production, by my colleagues, Mazzetto et al (2020), entitled “*Comparing the environmental efficiency of milk and beef production through life cycle assessment of interconnected cattle systems”*.

This piece is timely, from a regional perspective, as climate change impacts increase, the level of urgency to take action is increased. As such, policy makers and researchers need to be able to effectively assess environmental measures aimed at reducing impact, but also at increasing efficiency and food and income security. From a national perspective, this paper is also relevant given Costa Rica’s environmental commitments, coupled with reductions import tariffs for milk. In terms of the individual farms, this paper attempts to present results in as high a resolution as possible to avoid painting with a single broad brush.

I would like to thank you for considering our paper, and I look forward to hearing from you.

Sincerely,

Dr Colm Duffy

Marginal Abatement Cost Curves for Latin American Dairy Production: A Costa Rica case study

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Highlights

- First Marginal Abatement Cost Curve generated for Latin American dairy farms
- Priority efficient mitigation options vary across five dairy farm typologies
- Additional feed concentrate increases efficiency, but could displace emissions
- Silvopastoral and grazing management options show high potential

Table of Requested Edits

Editors Requests		
Number	**Request**	**Action**
1	the issue related to the general requirement of JCLEPRO is not well addressed.	We have eliminated all bulk referencing. This has been done in two ways, either the reference has been characterised in its own right, or, the most relevant reference has been utilised, with the redundant supporting references being removed. Where possible, the information has been edited to be delivered in as concise a manner as possible. We thank you for your patience with our editing efforts in this regard.

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Marginal Abatement Cost Curves for Latin American Dairy Production: A Costa Rica case study

Abstract

This study utilises data collected from Costa Rican dairy farmers to conduct a cradle to farm gate Life Cycle Assessment and the first Marginal Abatement Cost Curve (MACC) for dairy production in Latin America. Ninety dairy farms across five farm typologies were assessed, reflecting Costa Rica's diverse agroclimatic zones and varying degrees of dairy/beef specialisation. The efficacy and cost-effectiveness of specific mitigation measures depend on farm typology, but several promising technologies are identified that increase efficiency whilst substantially reducing emissions across most farms – in particular, measures that improve animal health and increase pasture quality. Pasture measures are synergistic with silvopastoral practises and are highly effective at emission mitigation, although relatively expensive. The replacement of lower quality by-product feeds with high quality concentrate feed is a cost-effective mitigation measure at farm level, but emission reductions could be negated by indirect land use change outside the scope of the MACC analyses. Achieving carbon neutrality at farm level is not likely to be possible for most farms, with the exception of extensive farm typologies. Not all measures are suitable in every context, and additional policy support will be needed to offset financial and technical challenges related to adoption. Results of this first tropical dairy MACC study are constrained by lack of high-resolution data, but they highlight the need for farm-typology-specific mitigation recommendations. Overall, there is a high potential for pasture improvement and silvopastoral measures to mitigate the globally significant contribution of Latin American livestock production to climate change.

Keywords: MACC; LCA; milk; footprint; climate mitigation

1. Introduction

The livestock sector accounts for 14.5% of all anthropogenic greenhouse gas (GHG) emissions that drive climate change (Gerber et al., 2013b). The main emissions from livestock production are methane (CH_4) from enteric fermentation and manure management (Rojas-Downing et al., 2017), and nitrous oxide (N_2O) from urine and dung deposition by grazing livestock, and manure management (Gerber et al., 2013a). In addition, applications of manure and synthetic fertilizer make up a sizeable proportion of N_2O emissions (Uwizeye et al., 2020). Land use change is a major global carbon dioxide (CO_2) emission source linked to livestock production (Gerber et al., 2013b), given livestock's large land footprint (Hayek et al., 2020). It is widely accepted that efforts to reduce livestock emissions are crucial to global climate stabilisation efforts (Frank et al., 2019). There are substantial opportunities for mitigation within livestock production systems (Smith et al., 2013), but significant investment is needed to realise these opportunities, especially in developing regions such as the Latin American and Caribbean (LAC) region (Herrero et al., 2016). Livestock production in LAC countries accounts for 1.9 gigatons CO_2e annually (FAO, 2020). Costa Rica is an exemplar of the challenges facing livestock systems in the LAC region because: (i) its diverse agroecosystems are representative of the wider LAC region; (ii) its agriculture sector is under increasing economic pressure to consolidate; (iii) a relatively developed research infrastructure facilitates detailed analyses of emission mitigation opportunities; (iv) its government has pledged to become carbon neutral (Flagg, 2018). The objective of this paper is to develop Marginal Abatement Cost Curves (MACC) to assess the feasibility of selected GHG mitigation measures for Costa Rican dairy farmers and illustrate the economic and technological feasibility of mitigation action across the wider LAC livestock sector.

1.1 Country Context

Costa Rica has both tropical and subtropical climates, with a dry season lasting from December to April, and a wet season from May to November (Central Intelligence Agency, 2019). Dairy production occurs in the cooler highlands and the warmer lowlands (MINAE and IMN, 2014). Agriculture contributes 5% to gross domestic product (GDP) in Costa Rica (World Bank, 2018), and accounts for 31-37% of national exports (OECD, 2017). The dairy subsector produced 1.2 million litres of milk in 2017, an increase of 16% since 2011 (FAO, 2017), and dairy products account for approximately 12% of value-added in the agriculture sector (SEPSA, 2016). Over 730,000 farms in Costa Rica are classed as dairy or dual-purpose (dairy and beef) (INEC, 2014), of which 48% are small producers (fewer than 15 animals) (Rodriguez-Lizano et al., 2018). Import tariffs of up to 66% on milk products and farm cooperatives maintain high milk prices nationally (OECD, 2017). Dos Pinos, the largest cooperative, accounts for almost 88% of sales value from Costa Rican dairy farms (Rodriguez-Lizano et al., 2018). Emissions of N_2O and CH_4 from agriculture make up almost 17% of Costa Rica's anthropogenic GHG emissions (MINAE and IMN, 2014).

The phasing out of tariffs as part of the DR-CAFTA (Dominican Republic – Central American Free Trade Agreement) will lower the overall price of milk, leaving small Costa Rican dairy farmers vulnerable. Recent research suggests that Costa Rican national production would decrease by up to 26% (Rodriguez-Lizano et al., 2018), with the demand gap being filled by imported milk. As Costa Rican dairy farmers strive to remain competitive in this economic environment, it is important that mitigation measures to reduce their environmental footprint also increase efficiency, and do not place undue economic hardship on small producers who will struggle to compete with larger domestic producers and imports (Rodriguez-Lizano and

Montero-Vega, 2016). For Costa Rica's carbon neutrality target, pathways to a zero-carbon economy by 2050 are being mapped (CRG, 2018). The national decarbonisation plan (CRG, 2018) envisages the promotion of circular economy livestock farming and the implementation of a biodigester program. Further, the plan also anticipates the implementation of low-carbon technologies for the majority of livestock producers by 2030. However, specific plans are still required.

1.2 Marginal Abatement Cost Curves for Mitigation Measures

A MACC for GHG emissions ranks mitigation measures according to their total cost (to the farmer) per kg of CO_2e abated(Moran et al., 2011), providing an evidence base for policymakers, in terms of target setting and policy implementation (Huang et al., 2016), and producers to make informed decisions with regards to mitigation options (Jiang et al., 2020). Eory et al (2018) claims that the development of agricultural MACCs is to both visualise "low hanging fruit", in terms of agricultural GHG mitigation opportunity, and to stimulate coherent discussion around the complex issues involved in agricultural emissions reduction.

Together with integrated assessment models (IAMs), the MACC is one of the major approaches utilised in the estimation of the economic impact of climate change mitigation (Clarke et al., 2014). IAMs are utilised to investigate implications of achieving climate mitigation goals (Van Vuuren et al., 2018), providing key information for policy makers and feeding into scientific reviews (Tavoni et al., 2015) such as the Intergovernmental Panel on Climate Change (IPCC) reports (Clarke et al., 2014). IAMs generate global longer term scenarios for regions or countries that can be used to inform policy (Tavoni et al., 2015), projecting emissions trajectories and economic implications of, *inter alia*, energy and land-use transitions (Clarke et al., 2014). Important assumptions are then made in relation to population and economic growth, available resources, technological change and mitigation policy (Clarke et al., 2014). By way of comparison, MACCs can assist policy makers in the development of a portfolio of mitigation technologies applicable at a variety of scales (e.g. national, regional, sectoral, farm), assisting in both macro- and micro- level decision making (Jiang et al., 2020). In this way, MACCs and IAMs represent complementary, rather than competing, decision support tools for policy makers.

MACC studies by Crijns-Graus (2004), and more recently Ahmed et al (2020), have investigated the implementation of mitigation measures on the global livestock sector towards 2050, with a focus on the main GHG sources and measures such as improved feed digestibility and improved nutrient and grassland management. The cost-effectiveness of mitigation measures and the level of adoption vary considerably across regions (Ahmed et al., 2020). Potential adoption is predicted to be low in developing countries (Crijns-Graus et al., 2004). Promising GHG mitigation measures for tropical systems that warrant further investigation in a MACC context include pasture restoration to enhance carbon sequestration and avoid deforestation (de Oliveira Silva et al., 2015), increasing green fodder and concentrate feeding, and anaerobic digestion of cattle manure (Sapkota et al., 2019). Whilst MACCs have been produced for agricultural sectors across several countries, such as the UK, Ireland, France, New Zealand, and China (Eory et al., 2018), as far as the authors are aware, no MACC has yet been published for LAC dairy systems. The aim of this paper is to fill that gap.

In summary, Costa Rican dairy farmers exemplify the challenges faced by LAC livestock systems to contribute towards climate stabilisation objectives, with declining economic margins in an increasingly competitive global market. This study employs data mining, stakeholder consultation and life cycle assessment (LCA) to parameterise a MACC for distinct dairy farm typologies in Costa Rica. The objective is to provide new evidence on the efficacy and economic efficiency of potential GHG mitigation measures for tropical and subtropical dairy systems.

2. Methods

2. 1 Overview

Despite relatively well-developed research infrastructure there is a paucity of published Costa Rican data for some aspects of costing and abatement potentials required for a MACC. Therefore, in-country experts were consulted to supplement data shortfalls. A list of potential mitigation measures was established after a review of the literature and consultation with key expert stakeholders in multiple meetings and workshops (see tables A.1, A.2, & A.3 for sources). Farm-level activity and financial data for these measures were collected through farm surveys. The efficacy of the measures at farm level was quantified based on parameters from the literature and following IPCC (2006) good practice guidelines for GHG accounting. Efficacy was expressed in relation to fat and protein corrected milk (FPCM) output, using LCA. Cost-effectiveness of each measure was then calculated based on net costs of implementation in relation to one kg FPCM (Gerber et al., 2011), and each kg of CO_2e abated.

2.2 Studied Farms

Farm data were collected by The Tropical Agricultural Research and Higher Education Centre (CATIE) for 95 specialised dairy farms in Costa Rica in two stages. The first stage sampled 45 farms in the provinces of Alajuela, Cartago, and San José between July and December of 2018 (Fig. 1). The second stage sampled 51 farms in the provinces of Limón, Guanacaste and Alajuela between March and May 2019. The semi-structured survey was conducted via face-to-face by technical specialists utilising the open source KoBoToolbox data collection tool. After cleaning and validation data for ninety farms was used in the study (n=90).

Figure 1. **The Costa Rican study area including the six survey regions of Alajuela, Guanacaste, San José, Cartago & Limón**

The surveyed farms were classified into five typologies defined by Vargas-Leitón et al (2013) based on analysis of 1086 dairy producers supplying Dos Pinos, Costa Rica’s largest dairy cooperative. Defining parameters were altitude, stocking rate, percentage of specialised breeds, amount of concentrate for milking cows and total milk production (Vargas-Leitón et al., 2013). Variable definitions and sample descriptive statistics pertinent to the farm LCA are summarised in Table A.4 The typologies are: (i) Specialised Dairy Extensive in the Lowland (SD_E_L) (35%), (ii) Specialised Dairy Intensive Lowland (SD_I_L) (22%), (iii) Specialised Dairy Semi-Intensive in the Uplands (SD_SI_U) (18%), (iv) Specialised Dairy Intensive in the Uplands (SD_I_U) (20%), and (v) Dual-purpose Extensive in the Lowlands (DP_E_L) (5%). The baseline farms were established using mean values for farm characteristics to establish the “average farm” in each farm typology.

Variables in the dataset included farm characteristics (e.g. farm area), farm inputs and consumption, and livestock outputs and herd composition. Farm inputs and consumption include annual fertiliser use in kilogrammes (kg) (urea, NPK, and other sources of N), electricity (kWh) and fuel consumption (L) and purchased animals (kg live weight). Livestock outputs and herd characteristics include average milk yield per cow in litres per day, the total number of animals in each herd cohort, and the live weight (kg) of animals sold.

2.3 Selection of appropriate mitigation measures

To select appropriate and feasible mitigation measures for the farm typologies a series of workshops and interviews were organised with experts to establish applicability, efficacy, on-farm costs and likely uptake. Workshops took place in September 2019 and January 2020 in San José and Cartago and included researchers, farm advisors and farmer groups, industry representatives, and policymakers (Table A.3). An in-situ panel of experts also specifically assessed cost, abatement potential, off-farm land sparing and overall fit for each typology. The shortlist of environmental measures selected for detailed MACC analysis is presented in Table 1. Measures are categorised into sub-groups, representing: technical measures (TM), efficiency measures (EF), pasture measures (PM), and manure measures (MM). Further detail on sources for abatement potential and cost are provided in tables A.1 and A.2.

Table 1. Mitigation measures shortlisted for evaluation in the Marginal Abatement Cost Curve

Name	Summary	Abbreviation
Anaerobic Digestion	Cost based on the CATIE system. Flares methane but does not convert to electricity	TM AD
Ventilation & Sprinklers	Heat stress reduction increases milk yield in hot periods	TM VS
Precision Feeding	Increased milk production with reduced crude protein fed	TM PF
Silvopastoral System	Based on a 20% of farm area afforested.	TM SP
Animal Health	Increase of milk production and reduced replacement rate	EF AH
Genetic Improvement	Increased milk output per cow	EF GI
Increase Concentrate	Increase amount of concentrate as single supplement by 25%	EF IC

Legumes	Increased crude protein in grazing, reduced concentrate, and reduced fertiliser application	PM LM
Improved Grasses	Forage based on grasses with higher yield and dry matter digestibility, reduced concentrate	PM IGV
Nutrient Management Plan	Reduction in nutrient application	PM NMP
Manure broadcast	Use of animal manure for forage production	MM BC

*TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure; MM= Manure Measure

2.4 Technical measures

The anaerobic digestion measure assumes that all excreta and effluent produced by housing animals (during milking and during adverse weather) is stored in the collection tank or digester bag. Costs related to the installation and management of the anaerobic digester were based upon reported costs from a commercial installation at CATIE (Casasola et al., 2018). The associated costs are related to small affordable anaerobic digesters, which flare methane, but do not include energy generation.

The ventilation and sprinkler measure assumes a reduction in heat stress during the dry season, increasing milk yield by 7.9% (Fournel et al., 2017). Costs for installation, management and water consumption were based on Gunn et al (2019). The precision feeding measure assumes a 2.6% increase in daily production from a 5% reduction in the long particle proportion of the daily ration (Sova et al., 2014). Costs for establishment and maintenance of precision feeding equipment are based on research by Piccioli-Cappelli et al (2019) and vendor information. For silvopastoral system establishment we assume that 20% of the farm area is planted, and account for CO_2 uptake by the growing trees as well as a proportionate reduction in livestock numbers. Species selection (*T. grandis*) and cost of establishment was based on silvopastoral research conducted by Pezo et al (2019) and Jimenez-Trujillo et al (2011).

2.5 Efficiency measures

Hospido and Sonesson (2005) indicate that a reduction in the instances of mastitis can improve milk yield and reduce milk losses. We assume that vaccination and more frequent animal health checks will reduce involuntary replacement rate by 10%, validated by the panel of in-country experts (summary of key parameters assumptions in Table A.5). Costs related to improved animal health, such as vaccination and more frequent health interventions, were established based on the relationship between total health cost and milk yield using linear regression of the parameters measured in baseline farms. Genetic improvement assumes a 10% increase in milk yield, linked with more concentrate feeding to satisfy higher energy requirements, informed by in-country experts and vendor information on costs (Table A.3). Increasing concentrate feeding assumes a 25% increase in high-quality concentrate in the ration, replacing lower quality feed supplements, linked with an increased milk yield. This is based on a concentrate response curve established using linear regression of the parameters measured in baseline farms. Costs related to concentrates are based on market prices.

2.6 Pasture & nutrient measures

The legumes measure assumes a 40% grass/legume mix, with fertilizer-N application capped at 50 kg ha^{-1} yr^{-1} for all farm typologies (Phelan et al., 2015). The implementation of improved grass varieties assumes a reduction in the use of concentrates and an increase in forage dry matter digestibility (Speedy and Sansoucy, 1998). It is assumed that the successful introduction of legumes and improved pasture increases average stocking density for extensive systems (DP_E_L and SD_E_L) to that achieved by the top 20% of most densely stocked farms within each typology. However, to keep these systems comparable with baseline farms, the total herd size was kept the same, and the area utilised reduced. Costs related to the establishment of legumes and improved grass varieties were assumed to be similar to the establishment of silvopastoral systems (Jimenez-Trujillo et al., 2011), utilising general labour rates (MTTS, 2019). For extensive systems, costs were calculated for land use based on increased stocking densities. Lastly, the implementation of a nutrient management plan assumed that farms would see an average 17% reduction in fertiliser use, based on previous MACC research by Eory et al. (2015). Savings related to the implementation of a nutrient management plan were based on market prices for fertiliser.

Animals graze outdoors all year round and are housed for between 4-6 hours a day, depending on whether farms are classified as upland or lowland. Therefore, relatively little manure is collected, and is diluted with wash water from the shed and milking parlour. Thus, most of the effluent collected is lightly contaminated, low dry matter content effluent, similar to dirty water (UK) (Arndt et al., 2020) or dairy shed effluent (New Zealand). Hence, based on expert judgement, many of the manure options applied to abate emissions from housed dairy systems were considered not likely to be cost-effective for Costa Rican farms.

2.7 Calculating mitigation efficacy

An attributional LCA was applied from cradle to farm gate to calculate the carbon footprint of milk production before (Fig. 2) and after application of mitigation measures, based on an adapted version of a cattle system LCA tool by Styles et al (2018) and, more recently, Mazzetto et al (2020). LCA is the calculation of inputs, outputs and environmental impacts of a system delivering a unit of product or service, accounting for all stages of raw material extraction, production, use and disposal (Rebitzer et al., 2004). Emissions of CH_4, N_2O (direct and indirect) and CO_2 to air were estimated from relevant activity data collected in the questionnaire surveys. Estimates of upstream burdens resulting from feed production, electricity generation, diesel supply and the manufacture of synthetic fertiliser were derived from Ecoinvent (version 3.4) (Wernet et al., 2016). Enteric CH_4 and manure management CH_4 and N_2O emissions were calculated using IPCC Tier 2 equations (IPCC, 2006) and Tier 2 calculation of energy intake and Nitrogen (N) excretion according to dietary crude protein (CP) intake. Soil N_2O emissions are derived from N Pasture Range and Paddock (PRP) excretion during grazing, and the application of synthetic fertiliser and manure spreading (IPCC Tier 1). Indirect emissions of N_2O were calculated based on NH_3 emission and N-leaching factors from national inventory reporting from Ireland (Duffy et al., 2014) and the UK (Misselbrook et al., 2014). Emissions are presented as kg of CO_2e according to 100-year global warming potentials of 1, 25 and 298 per kg of CO_2, CH_4 and N_2O emitted, respectively (IPCC, 2006).

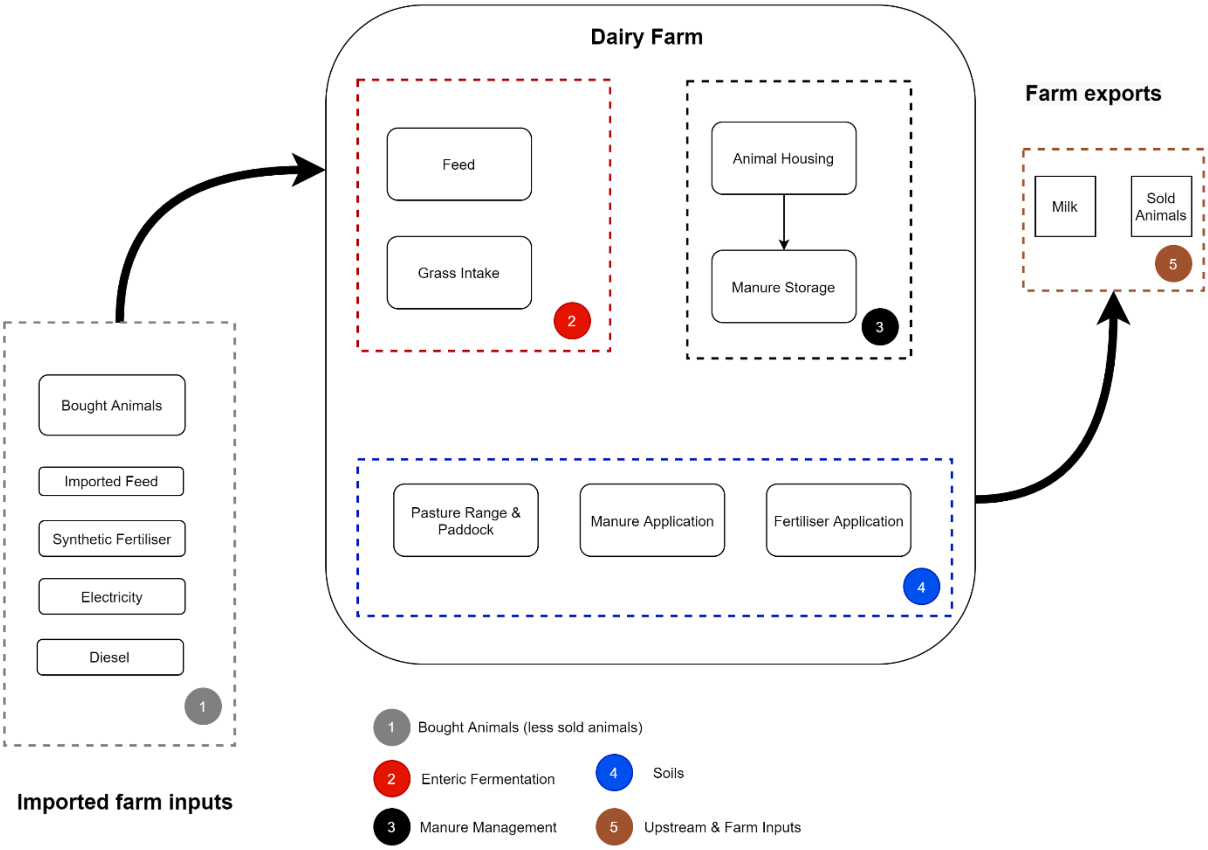


Figure 2. System boundaries applied in the LCA, from cradle (material extraction for farm inputs) through to the farm-gate

Calculations utilised attributional LCA to derive carbon footprints per kg of FPCM (Gerber et al., 2011) across all farms. Farm emissions were allocated to milk production (rather than animal live weight production) based on the respective gross energy content of milk and live weight exported from each farm (Mazzetto et al., 2020). Activity data and GHG emissions were averaged across farms within each farm typology to generate a baseline farm for each typology. Fig 3. presents the carbon footprint of each of the baseline farm types.

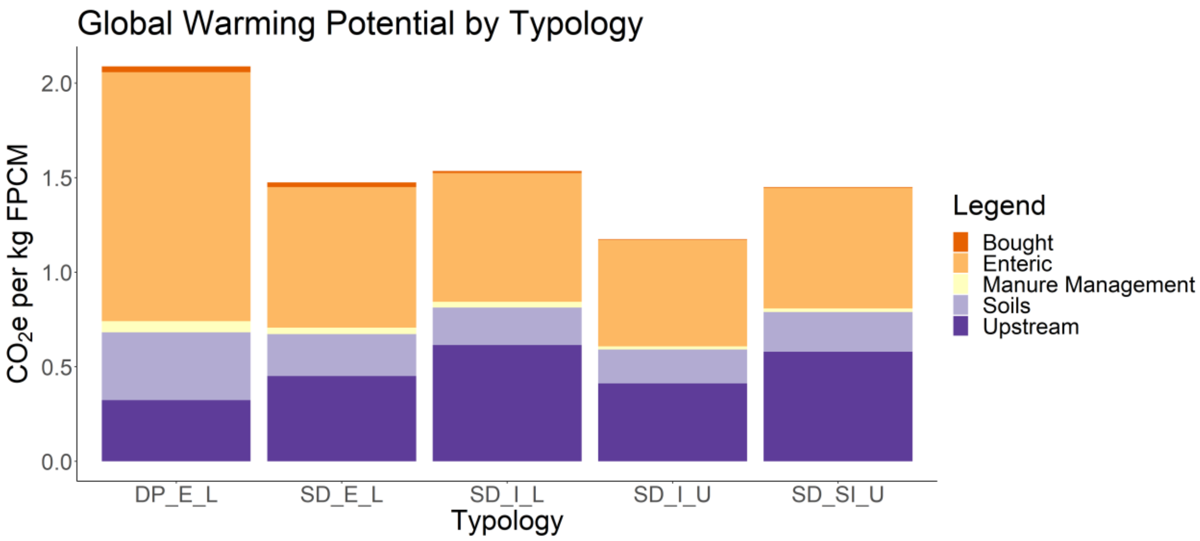


Figure 3. Average carbon footprint of milk produced across the five main dairy farm typologies, broken down by main sources: Bought-in animals, enteric methane, manure management emissions, soil emissions and emissions from upstream manufacture and transport of inputs such as fertilisers

*DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands

2.8 Costing

Net additional variable and fixed costs at the farm level were calculated for each mitigation option. Variable costs comprise inputs such as feed, fertilizer, labour, health, maintenance, transport, and services. Fixed costs comprise investment in buildings and machinery including financial costs and depreciation. The cost of investment in mitigation technologies was included in financial costs and assumed as amortisation of initial costs by the farmers (five years amortisation to install TM PF, TM SP, MM BC; fifteen years amortisation to install PM NMP). The sources for cost calculation can be found in table A.2. The base year for costs was 2019, and prior cost estimates were adjusted according to the inflation rate. The abatement cost was calculated as an increase in cost per unit of reduction in kg CO_2e from the mitigation options (based on the LCA results). The equation used to estimate abatement cost is as follows:

$$Abatement\ cost_i = \frac{Cost_i - Benefit_i}{reduced\ GHGE_i} \times -1$$

Where $Abatement\ cost_i$ is the cost of mitigation measure *i*, *Cost* is the cost of implementation, *Benefit* is the additional return received and reduced $GHGE_i$ is the expected GHG reduction.

3. Results & Discussion

Results of the MACC are presented in Table 2 and Fig. 4 & 5, whilst Fig. 6 presents a contextual feasibility assessment of each of the mitigation measures in terms of cost, efficacy, potential for land sparing, and overall fit for each of the farm typologies. Cost and abatement potential in Fig. 6 are a direct reflection of the MACC presented in Table 2 and Fig. 4 and 5, while off-farm land sparing, and overall typology fit is based on expert opinion (Table A.3).

Table 2. Marginal Cost and kg CO_2 abatement per kg of FPCM across the assessed measures

		Typologies									
		DP_E_L		**SD_E_L**		**SD_I_L**		**SD_I_U**		**SD_SI_U**	
Code	**Measures**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**
TM AD	Anaerobic Digestion	0.06	0.07	0.09	0.03	0.07	0.03	0.08	0.02	0.06	0.03
TM V&S	Ventilation or sprinklers	0.08	0.05	0.04	0.03	-0.06	0.03	-0.11	0.02	-0.09	0.03
TM PF	Precision Feeding	0.04	0.04	0.12	0.03	0.06	0.03	-0.01	0.02	0.03	0.02
TM SP (20%)	Silvopastoral	0.05	1.57	0.11	0.49	0.14	0.36	0.17	0.24	0.15	0.34
EF AH	Animal Health	-0.11	0.27	-0.12	0.16	-0.15	0.16	-0.2	0.12	-0.17	0.15
EF GI	Genetic Improvement	1.38	0.07	1.04	0.05	0.53	0.07	0.63	0.05	0.54	0.07
EF IC	Increase Concentrate	-0.09	0.36	-0.05	0.21	-0.9	0.27	-0.11	0.21	-0.11	0.25
PM IGV	Improved Grass Variety	0.20	0.22	-0.12	0.1	0.46	0.07	-0.64	0.05	0.04	0.06
PM LM	Legume	0.01	0.43	0.16	0.2	0.19	0.16	0.04	0.12	0.1	0.15
PM NMP	Nutrient Management Plan	-0.14	0.03	-0.1	0.05	-0.08	0.04	-0.02	0.02	-0.02	0.12
MM BC	Broadcast	10.17	< 0.0	18.63	< 0.0	21.67	< 0.0	33.18	< 0.0	33.96	< 0.0

*TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure; MM= Manure Measure
**DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands
***AP =Abatement Potential kg CO_2e per kg of FPCM milk; Cost= AP Cost in $USD per kg of milk

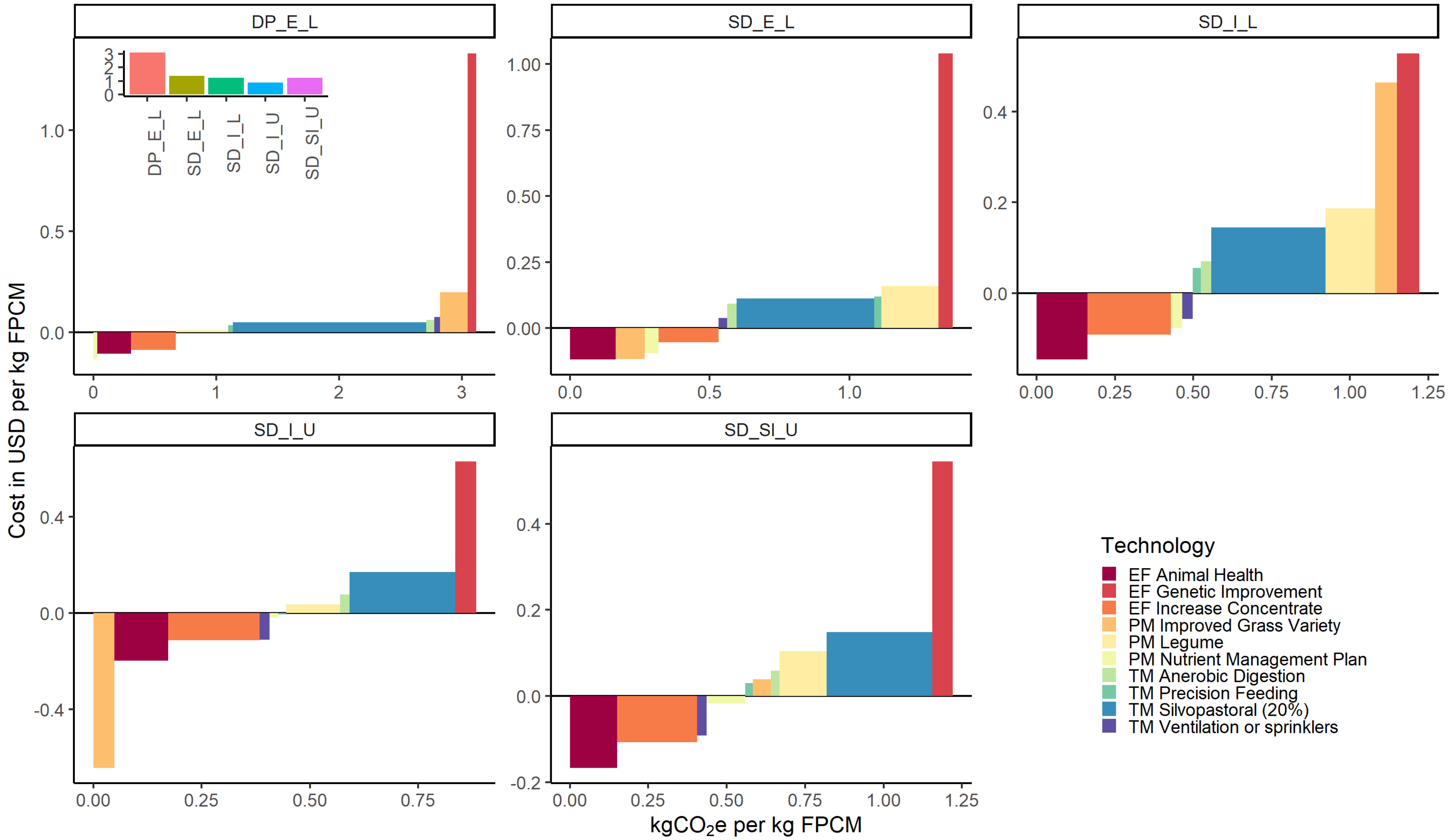

DP_E_L
SD_E_L
SD_I_L
SD_I_U
SD_SI_U
Cost in USD per kg FPCM
kgCO$_2$e per kg FPCM
1.0
0.5
0.0
0
1
2
3
DP_E_L
SD_E_L
SD_I_L
SD_I_U
SD_SI_U
1.00
0.75
0.50
0.25
0.00
0.0
0.5
1.0
0.4
0.2
0.0
0.00
0.25
0.50
0.75
1.00
1.25
0.4
0.0
-0.4
0.00
0.25
0.50
0.75
0.4
0.2
0.0
-0.2
0.00
0.25
0.50
0.75
1.00
1.25
Technology
EF Animal Health
EF Genetic Improvement
EF Increase Concentrate
PM Improved Grass Variety
PM Legume
PM Nutrient Management Plan
TM Anerobic Digestion
TM Precision Feeding
TM Silvopastoral (20%)
TM Ventilation or sprinklers

Figure 4. **Marginal abatement cost curve for each typology, with costs and abatement potentials related to one kg of FPCM. The top left inset graph summarises the total abatement potential per farm typology related to one kg of FPCM**

*TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure
**DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands
*** TM AD=Anaerobic Digestion; TM V&S=Ventilation or sprinklers; TM PF=Precision Feeding; TM SP (20%)=Silvopastoral; EF AH=Animal Health; EF CB=Genetic Improvement; EF IC=Increase Concentrate; PM IGV=Improved Grass Variety; PM LM=Legume; PM NMP=Nutrient Management Plan; MM BC=Broadcast

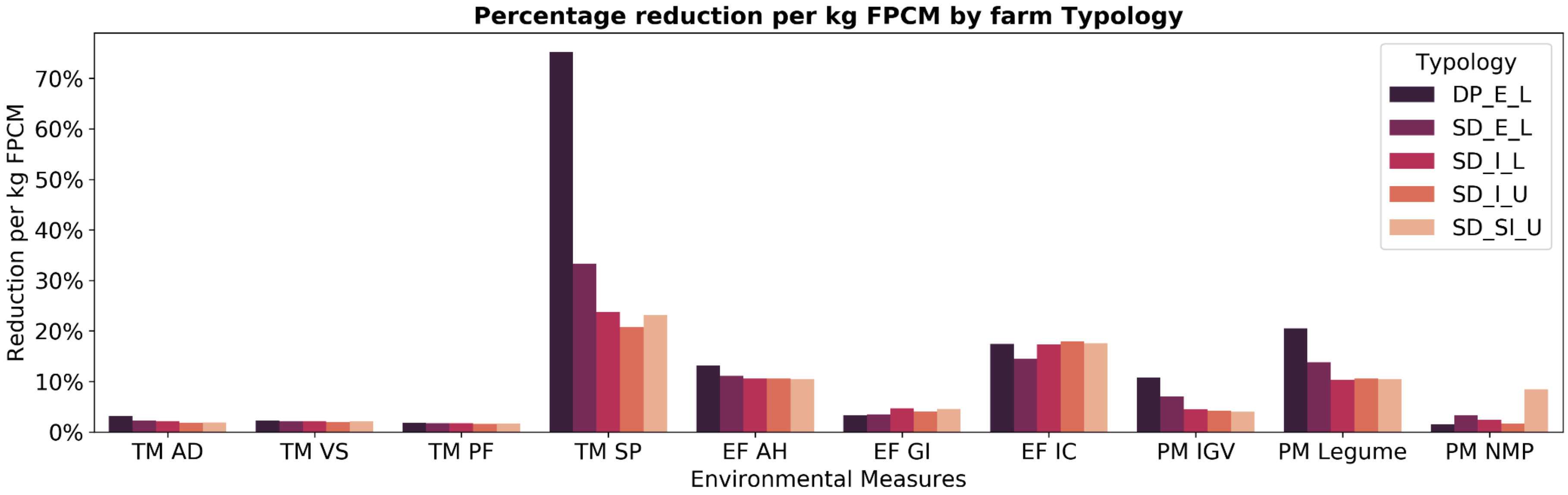


Figure 5. **Proportional abatement per kg of FPCM per mitigation measure relative to baseline emissions burden by farm typology**

*TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure
**DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands
*** TM AD=Anaerobic Digestion; TM V&S=Ventilation or sprinklers; TM PF=Precision Feeding; TM SP (20%)=Silvopastoral; EF AH=Animal Health; EF CB=Genetic Improvement; EF IC=Increase Concentrate; PM IGV=Improved Grass Variety; PM LM=Legume; PM NMP=Nutrient Management Plan; MM BC=Broadcast

3.1 Technical measures

Anaerobic digestion for the production of biogas is recognised as an effective approach to mitigation of GHG emissions, especially when utilising waste or secondary feedstock (Bacenetti et al., 2016). However, the major challenge is the cost of implementation and technical capacity (Mwakaje, 2008). Here, anaerobic digestion implementation modestly increased costs across all farm typologies. Previous estimates by Moran et al (2011) also present a similar trend of modest additional costs to implement anaerobic digestion on farms . Based on pricing information provided by CATIE (Casasola et al., 2018), basic *anaerobic digestion* systems can be implemented relatively cheaply in Costa Rica's warm climate. However, abatement potential was limited for all farm typologies due to the limited amount of housed manure production. Further, the diluted effluent (slurry and dirty water) has a relatively low methane yield potential. Manure-based anaerobic digestion systems typically utilise slurry, as opposed to effluent, for methane production (Lovarelli et al., 2019). Abatement potential per kg FPCM is higher for dual-purpose farms (DP_E_L) owing to their lower milk yields. Overall, quantities of house manure are not sufficient to make *anaerobic digestion* cost-effective in these tropical systems where animals mostly graze outdoors and in the absence of useful energy generation.

Climatic conditions that result in heat stress can have a significant impact on animal health and production (Fournel et al., 2017). *Ventilation and sprinklers* are cost-effective across intensive farm typologies, reducing costs by $0.11 per kg of milk for intensive upland systems owing to increased milk yield. However, the average abatement potential is relatively low (0.03kg of CO_2e per kg of milk) and in-country experts indicated that these systems are not applicable for highland typologies. Cows in highland areas are only brought in for milking as they do not suffer heat exposure to the same degree as farms in lowland areas. Lowland farms do keep cows housed for slightly longer periods given the consistently higher temperatures experienced in these areas.

Precision Feeding is an attempt to reduce the mismatch between animal feed and the nutritional requirement of the animal (Piccioli-Cappelli et al., 2019). However, utilisation of precision feeding technologies represents a significant investment for dairy farmers (Borchers and Bewley, 2015). Here, *Precision feeding* is cost-effective only for intensive upland systems with higher output, achieving an average abatement of 0.03kg of CO_2e per kg of milk. Banhazi et al (2012) claim that current dissemination of various precision livestock technologies is fragmented and producers require additional services related to installation and maintenance of software, and the interpretation of data. Further, a study conducted by Gargiulo et al (2018) on the adoption of current precision technologies by Australian dairy farmers found that larger dairy farmers, with herd sizes exceeding 500 dairy cows, were most likely to adopt precision technologies. Given the cost and the relatively small size of dairy farms in Costa Rica, it is likely that this technology will not be feasible for most farms.

Silvopastoral systems integrate trees with livestock systems and provide benefits related to soil fertility and carbon sequestration, shade for animals, timber and non-timber products, and biodiversity benefits (McGroddy et al., 2015). The MACC results indicate a high potential for abatement, especially for extensive farms with relatively low stocking rates. Emissions are reduced by up to 70% for dual purpose farms (Fig. 5). However, the significant establishment costs are a barrier to adoption of silvopastoral systems (Pezo et al., 2019). A review of agroforestry adoption studies conducted by Pattanayak et al (2003) highlighted the knowledge-intensive nature of *silvopastoral systems*, finding that the availability of extension services has a significant impact on adoption. A potential solution may entail payments for environmental services (Dinesh et al., 2015), which have been utilised in Columbia, Costa Rica and Nicaragua in the past (Pezo et al., 2019).

3.2 Efficiency measures

Mastitis reduces milk yield and taints the milk produced (Hospido and Sonesson, 2005). In addition, lameness and calving problems are also major causes of death in the dairy industry (Hristov et al., 2013c). The *Animal Health* measure is cost-effective for all farm typologies, reducing production costs by an average of \$0.15 per kg FPCM, and up to \$0.20 per kg FPCM for intensive upland farms. The average abatement potential was 0.18kg of CO_2e per kg FPCM, rising to 0.27kg of CO_2e per kg FPCM for dual-purpose farms. These results demonstrate that *Animal Health* interventions and reducing the number of replacements can have a clear benefit in terms of both economic efficiency and emissions reductions across all typologies.

Genetic Improvement to increase milk yield has resulted in high performing (Hansen, 2000), heavier, dairy cows (Hristov et al., 2013c). However, these cows have different nutritional requirements (Hristov et al., 2013c) and a significant up-front capital investment. In addition, high yielding breeds may represent a significant risk to the farmer if the necessary nutrition, health and physical environment requirements cannot be met (Madalena, 2007). The expected rapid gains in production often fall short of expectation (Hristov et al., 2013c). These new results show that, for Costa Rican dairy farmers, *Genetic improvement* is cost-prohibitive across all typologies, costing up to \$1.38 per kg FPCM for dual-purpose farms (Table 2). For other farm typologies, the costs ranged from \$1.04 to \$0.53 per kg of milk. Average abatement potential of 0.06kg of CO_2e per kg FPCM is small relative to the cost. Furthermore, research by Madalena (2007) indicates that the potential health problems associated with these breeds are more pronounced in hotter regions. So, lowland farms in Costa Rica would struggle to provide the conditions necessary for improved breeds to achieve their genetic potential. Further research is therefore required regarding the optimal cattle breeds for Costa Rica diverse agroclimatic conditions.

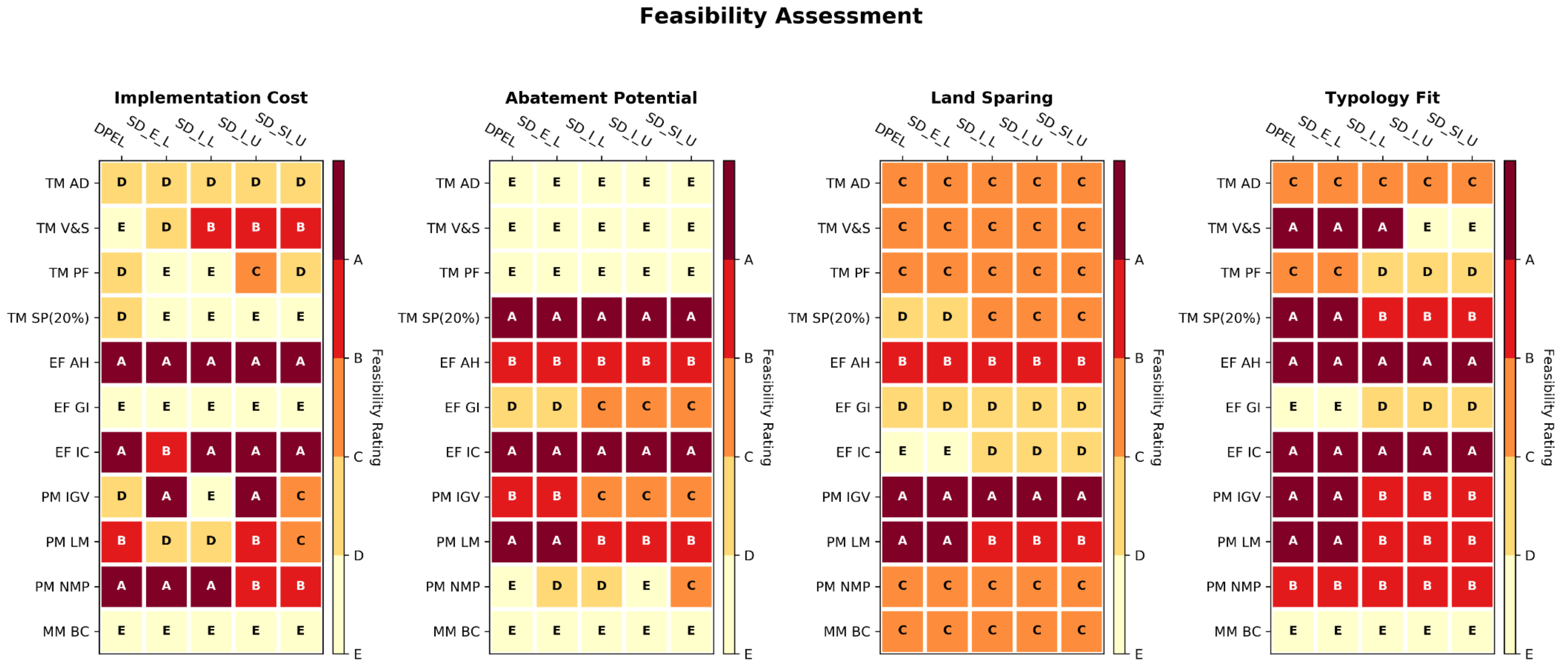
Increasing Concentrate proportions where forage quality is low has previously been shown to decrease CH_4 emissions (Gerber et al., 2013a). High-quality (more energy-dense or more digestible) diets provide more energy for production and increase animal performance, lowering CH_4 emissions (Hristov et al., 2013b) Further, the inclusion of high quality concentrate can, potentially, lower emissions in and of itself (Knapp et al., 2014). These MACC results indicate that the increased cost of providing greater quantities of imported high-quality concentrate is offset by increased animal-level productivity across all farm typologies. On average, increasing the proportion of concentrate in the diet by 25% decreased costs by \$0.09 per kg of milk through increased yields per cow (Table 2). In terms of abatement potential, emissions were reduced by an average of 0.26 kg of CO_2e per kg FPCM. However, the increase in efficiency at animal- and farm-level comes at a cost of off-farm cropland requirement with potential food security implications (Ripple et al., 2014) (Fig. 6). Recent studies in Costa Rica by Mazzetto et al (2020) and the UK by Styles et al (2018) have shown that reducing milk footprints via intensification can increase emissions elsewhere via indirect land-use change to supply additional concentrate feed and via reduced dairy-beef output. Results on concentrate feed must therefore be interpreted very cautiously owing to the constrained scope of MACC analyses.

3.3 Pasture & nutrient supply measures

Improved Grass Varieties and *Legumes* in pasture management have significant abatement potential and apply to all farm typologies (Table 2; Fig. 4 & 5). Henderson et al (2017) previously highlighted the abatement potential of grassland management and legume utilisation in the LAC region, whilst increasing animal productivity through forage improvement has been demonstrated as one of the most effective mitigation strategies available to dairy producers (Gerber et al., 2013a). The MACC indicated that the average abatement potential of *pasture legumes* (0.21 kg of CO_2e per kg of milk) is twice that of the *Improved Grass Variety* measure. However, establishing legume pastures increased cost for all typologies, by \$0.10 per kg FPCM on average, and switching to *Improved Grass Varieties* was cost-prohibitive for dual-purpose and intensive lowland farms – but decreased costs for other typologies by an average of \$0.24 per kg FPCM (Table 2). The conservative modelling approach adopted in this study may under-represent improvements in milk yield associated with better quality forage (Hristov et al., 2013a). In addition, the potential to increase stocking density can result in spared land that can be utilised for additional income generation and/or mitigation action. Further, both measures are likely to reduce the need for concentrate usage, offsetting the financial penalty of both measures, and reducing the risk of indirect land-use change impacts associated with concentrate production (Fig. 6). However, barriers to adoption of pasture legumes by farmers will need to be overcome. These challenges include a lack of legume persistence under heavy grazing, low availability and cost of commercial seed, and a lack of farmer knowledge and training (Muir et al., 2017).

Implementation of *Nutrient Management Planning* requires an assessment of the overall farm nutrient status and assessment of the application, nutrient inventory and crop requirements. Based on this information, management options and optimum application of nutrients are calculated (Beegle et al., 2000). Evidence suggests that the introduction of nutrient budgeting tools can reduce nutrient application inefficiencies and associated costs and environmental burdens (Gourley et al., 2007). The current MACC analysis highlights a potential saving for farmers from the associated reduction in fertiliser. *Nutrient management planning* is cost-effective for all farm typologies (Table 2), especially extensive farm typologies, and achieves abatement of between 0.12 and 0.02kg of CO_2e per kg FPCM (Fig. 3). Widespread adoption of nutrient management planning may require additional extension or consulting services that could increase the costs for farmers, potentially reducing uptake (Beegle et al., 2000). In terms of overall fit, this measure could still lead to significant abatement and a reduction in costs for the farmer.

In Costa Rica, urine and faeces captured whilst animals are housed for feeding and milking are combined with water from the milking parlour and stable. These dilute effluents, known as “purines”, are then allowed to drain into the fields (Tretti, 2019). Although the cost of the basic infrastructure necessary to implement *Broadcast Manure* application to fields is low, the quantity of effluent produced by animals housed between 4-6 hours a day is too small to make this measure cost-effective for any of the typologies (Table 2). In addition, the GHG abatement potential associated with this measure is very low (Fig. 4). However, other impacts such as eutrophication may be reduced, which could justify implementation of this measure from a wider environmental protection perspective.



Implementation Cost

	DPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	D	D	D	D	D
TM V&S	E	D	B	B	B
TM PF	D	E	E	C	D
TM SP(20%)	D	E	E	E	E
EF AH	A	A	A	A	A
EF GI	E	E	E	E	E
EF IC	A	B	A	A	A
PM IGV	D	A	E	A	C
PM LM	B	D	D	B	C
PM NMP	A	A	A	B	B
MM BC	E	E	E	E	E

Abatement Potential

	DPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	E	E	E	E	E
TM V&S	E	E	E	E	E
TM PF	E	E	E	E	E
TM SP(20%)	A	A	A	A	A
EF AH	B	B	B	B	B
EF GI	D	D	C	C	C
EF IC	A	A	A	A	A
PM IGV	B	B	C	C	C
PM LM	A	A	B	B	B
PM NMP	E	D	D	E	C
MM BC	E	E	E	E	E

Land Sparing

	DPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	C	C	C	C	C
TM V&S	C	C	C	C	C
TM PF	C	C	C	C	C
TM SP(20%)	D	D	C	C	C
EF AH	B	B	B	B	B
EF GI	D	D	D	D	D
EF IC	E	E	D	D	D
PM IGV	A	A	A	A	A
PM LM	A	A	B	B	B
PM NMP	C	C	C	C	C
MM BC	C	C	C	C	C

Typology Fit

	DPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	C	C	C	C	C
TM V&S	A	A	A	E	E
TM PF	C	C	D	D	D
TM SP(20%)	A	A	B	B	B
EF AH	A	A	A	A	A
EF GI	E	E	D	D	D
EF IC	A	A	A	A	A
PM IGV	A	A	B	B	B
PM LM	A	A	B	B	B
PM NMP	B	B	B	B	B
MM BC	E	E	E	E	E

Figure 6. **Contextual feasibility framework for the assessment of environmental measure fit to farm typology**

*A = Very Suitable; B = Suitable; C = Somewhat Suitable; D = Somewhat Unsuitable; E = Not Suitable at all

**TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure

***DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands

**** TM AD=Anaerobic Digestion; TM V&S=Ventilation or sprinklers; TM PF=Precision Feeding; TM SP (20%)=Silvopastoral; EF AH=Animal Health; EF CB=Genetic Improvement; EF IC=Increase Concentrate; PM IGV=Improved Grass Variety; PM LM=Legume; PM NMP=Nutrient Management Plan; MM BC=Broadcast

**** TM AD=Anaerobic Digestion; TM V&S=Ventilation or sprinklers; TM PF=Precision Feeding; TM SP (20%)=Silvopastoral; EF AH=Animal Health; EF CB=Genetic Improvement; EF IC=Increase Concentrate; PM IGV=Improved Grass Variety; PM LM=Legume; PM NMP=Nutrient Management Plan; MM BC=Broadcast

3.4 Looking Forward

Effective strategies for mitigation are highly context-specific. Diversity among dairy farms in Costa Rica reflects differing agroclimatic zones and degrees of dairy/beef specialisation. Mitigation options must be assessed for individual typologies. From the feasibility assessment, it is evident that there is no universal mitigation practice (Fig. 6). Results from the MACC must also take into consideration the potential co-benefits that may arise. For example, the implementation of legumes and improved pasture on more extensive farm typologies will likely leave spared land for additional income generation/mitigation activities. The utilisation of this land for synergistic mitigation measures, such as silvopastoral measures, can reduce the overall emissions burden.

Some cost-effective mitigation measures may need to be treated with caution. For example, the replacement of lower quality co-products with high quality concentrate feed. Emissions reductions may be negated by indirect land use change driven by increased crop demand, which is beyond the scope of this MACC. We strongly recommend that MACC analyses are adapted to capture important indirect consequences of farm changes, for example using a consequential (rather than attributional) LCA approach to calculate net emission savings (Styles et al., 2018).

Finally, as can be seen from the results and the contextual feasibility assessment, dairy farmers in most typologies are unlikely to achieve carbon neutrality at the farm level, with the notable exception of dual-purpose farms. However, this does not mean that farm emissions should not be significantly reduced. Many of the measures here, with further investigation and supportive policy, can increase efficiency, reduce costs and mitigate emissions. Considering that Costa Rican dairy farmers face an uncertain future, increasing farm economic and environmental sustainability is a priority. To reach carbon neutrality at a national level, a much wider view of interconnected production systems must be taken (Mazzetto et al., 2020), and other opportunities within the agriculture and land use sector, and downstream sectors, must be found to reduce and offset emissions. Significant potential exists to improve efficiency and eliminate waste from production to final consumption. The IPCC (2019a) reported that food waste alone accounts for up to 10% of global anthropogenic GHG emissions.

Recommendations for research and policy

The key research and policy recommendations arising from the results of this work are summarised below:

Improving animal health is a clear win-win measure that reduces costs and GHG emissions; a farmer awareness campaign highlighting economic savings of healthy animals, e.g. via extension services, could drive deployment of this mitigation measure.

Apparent cost and emission savings arising from replacement of by-products with concentrate feeds goes against the principle of circularity (unless higher-value uses can be found for by-products) and risks driving indirect land use change. In light of these risks, no policy recommendations can be made on this measure until further research validates animal-performance and quantifies indirect effects of crop system expansion.

Dilute purines (slurry & effluent) and short housing times mean that anaerobic digestion and efficient manure spreading technologies are not cost-effective GHG mitigation options in Costa Rica. However, the potential water quality impact arising from the current practise of draining purines into fields warrants further research to determine whether specific mitigation measures are required.

The introduction of forage legumes and silvopastoral practises could drive considerable GHG mitigation, to the point of farm-level carbon neutrality for extensive dual-purpose systems. However, based on limited available data, implementation costs appear high. Cost-effective integration of legume forages and silvopastoral practises should be a priority for future research and policy.

Reaching carbon neutrality may not always desirable at farm level. Policies and management practises should be based on holistic evidence including farm- and product-level emissions and removals (e.g. this MACC study), alongside land use efficiency and aforementioned indirect consequences of changes on inter-connected beef and cropping systems.

4. Conclusion

Costa Rica faces the twin challenges of becoming carbon neutral by 2050 and the impact on dairy farmers from the reduction of tariffs on dairy imports. Local dairy producers must reduce their emissions and remain competitive in an increasingly challenging market. Utilising primary data to establish baseline farms and a combination of literature review and expert judgement to assess mitigation potential, this study represents the first dairy farm MACC for any LAC country.

Several promising technologies can increase efficiency for farmers whilst reducing emissions. Measures that improve animal health and increase pasture quality are highlighted as particularly effective. Pasture improvement (incorporation of legumes or improved grass varieties) presents significant synergistic potential with silvopastoral practises that are highly effective at reducing net emissions, especially for extensive farm typologies. The replacement of lower quality co-product feeds with high quality concentrate feed appears to be an effective mitigation measure at the farm level, but this could be negated by indirect land use change which was outside the scope of the MACC methodology. We recommend further analyses be undertaken with a broader system boundary to consider inter-system consequences of mitigation options, in particular on interconnected beef and cropping systems.

Achieving carbon neutrality at farm level is not likely to be possible for most farm typologies, with the exception of dual-purpose farms. But many measures that improve efficiency could spare land and facilitate carbon offsetting needed to achieve carbon neutrality at national level. Not all measures are suitable in every context, and several promising measures would need additional policy support to be widely deployed, including financial and technical assistance at farm level. Overall, there is high potential for pasture improvement and silvopastoral measures to mitigate the contribution of livestock production in LAC to climate change.

Declaration

The authors confirm that this study has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Declaration of Interest

None.

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References

Ahmed, J., Almeida, E., Aminetzah, D., Denis, N., Henderson, K., Katz, J., Kitchel, H., Mannion, P., 2020. Agriculture and climate change reducing emissions through improved farming practices.

ARESEP, 2017. Pliegos tarifarios del servisio de acueducto, AyA 2017-2021 [WWW Document]. URL https://aresep.go.cr/tarifas/tarifas-vigentes/2199-tarifa-acueducto-aya-2017-2021 (accessed 12.6.19).

Arndt, C., Misselbrook, T.H., Vega, A., Gonzalez-Quintero, R., Chavarro-Lobo, J.A., Mazzetto, A.M., Chadwick, D.R., 2020. Measured ammonia emissions from tropical and subtropical pastures: A comparison with 2006 IPCC, 2019 Refinement to the 2006 IPCC, and EMEP/EEA (European Monitoring and Evaluation Programme and European Environmental Agency) inventory estimates. J. Dairy Sci. 103, 6706–6715. https://doi.org/10.3168/jds.2019-17825

Bacenetti, J., Sala, C., Fusi, A., Fiala, M., 2016. Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable. Appl. Energy 179, 669–686. https://doi.org/10.1016/j.apenergy.2016.07.029

Banhazi, T.M., Babinszky, L., Halas, V., Tscharke, M., 2012. Precision livestock farming: Precision feeding technologies and sustainable livestock production. Int. J. Agric. Biol. Eng. https://doi.org/10.3965/j.ijabe.20120504.006

Beegle, D.B., Carton, O.T., Bailey, J.S., 2000. Nutrient Management Planning: Justification, Theory, Practice.

Benchmark, 2019. The Cattle Site [WWW Document]. URL http://thecattlesite.com/ (accessed 11.6.19).

Borchers, M.R., Bewley, J.M., 2015. An assessment of producer precision dairy farming technology use, prepurchase considerations, and usefulness. J. Dairy Sci. 98, 4198–4205. https://doi.org/10.3168/jds.2014-8963

Casasola, F., Villanueva, C., Ibrahim, M., Lombo, D., 2018. Tecnologías relevantes para la gestión integral del estiércol en fincas ganaderas de Costa Rica. Turrialba, Costa Rica, CATIE.

Central Intelligence Agency, 2019. Costa Rica Fact Summary. World Fact B. 1.

Chen, L., de Haro Marti, M., Gray, W., Neibling, H., Chahine, M., Yadanaparthi, S., 2013. On-Farm Comparison of Two Liquid Dairy Manure Application Methods in Terms of Ammonia Emission, Odor Emission, and Costs [WWW Document]. URL https://lpelc.org/on-farm-comparison-of-two-liquid-dairy-manure-application-methods-in-terms-of-ammonia-emission-odor-emission-and-costs/ (accessed 9.28.19).

Clarke, L.K., Jiang, K., Akimoto, M., Babiker, G., Blanford, K., Fisher-Vanden, J.C., Hourcade, V., Krey, E., Kriegler, A., Löschel, D., McCollum, S., Paltsev, S., Rose, P.R., Shukla, M., Tavoni, B.C., van der Zwaan, C., van Vuuren, D.P., 2014. Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Craig, K., 2017. The Farm Management Handbook 2017/18. SAC Consulting, Edinburgh.

CRG, 2018. Decarbonization Plan Government of Costa Rica Decarbonization Plan Commitment of the Bicentennial Government.

Crijns-Graus, W.H.J., Harmelink, M., Hendriks, C., 2004. Marginal greenhouse gas abatement curves for agriculture. Utrecht.

de Oliveira Silva, R., Barioni, L.G., Albertini, T.Z., Eory, V., Topp, C.F.E., Fernandes, F.A., Moran, D., 2015. Developing a nationally appropriate mitigation measure from the greenhouse gas GHG abatement potential from livestock production in the Brazilian Cerrado. Agric. Syst. 140, 48–55. https://doi.org/10.1016/j.agsy.2015.08.011

Dinesh, D., Frid-Nielsen, S., Norman, J., Mutamba, M., Maria, A., Rodriguez, Loboguerrero Campbell, B., 2015. Is Climate-Smart Agriculture effective? A review of selected cases.

Duffy, P., Hanley, E., Hyde, B., O'brien, P., Ponzi, J., Cotter, E., Black, K., 2014. Ireland national inventory report 2012 greenhouse gas emissions 1990-2010 reported to the united nations framework convention on climate change. Wexford, Ireland.

Eory, V., MacLeod, M., Topp, C.F.E., Rees, R.M., Webb, J., McVittie, A., Wall, E., Borthwick, F., Watson, C., Waterhouse, A., others, 2015. Review and update the UK Agriculture Marginal Abatement Cost Curve to assess the greenhouse gas abatement potential for the 5th carbon budget period and to 2050. Assess Abat. Potential 5th Carbon Final Rep. Submitt. Proj. Contract "Provision Serv. to Rev. Updat. UK Agric. MACC toBudget Period to 2050.

Eory, V., Pellerin, S., Carmona Garcia, G., Lehtonen, H., Licite, I., Mattila, H., Lund-Sørensen, T., Muldowney, J., Popluga, D., Strandmark, L., Schulte, R., 2018. Marginal abatement cost curves for agricultural climate policy: State-of-the art, lessons learnt and future potential. J. Clean. Prod. 182, 705–716. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.01.252

FAO, 2020. Transforming the livestock sector through the Sustainable Development Goals. Rome, Italy.

FAO, 2017. FAOSTAT.

Flagg, J.A., 2018. Carbon neutral by 2021: The past and present of Costa Rica's unusual political tradition. Sustain. 10. https://doi.org/10.3390/su10020296

Fournel, S., Ouellet, V., Charbonneau, É., 2017. Practices for alleviating heat stress of dairy cows in humid continental climates: A literature review. Animals 7, 1–23. https://doi.org/10.3390/ani7050037

Frank, S., Havlík, P., Stehfest, E., van Meijl, H., Witzke, P., Pérez-Domínguez, I., van Dijk, M., Doelman, J.C., Fellmann, T., Koopman, J.F.L., Tabeau, A., Valin, H., 2019. Agricultural non-CO2 emission reduction potential in the context of the 1.5 °C target. Nat. Clim. Chang. 9, 66–72. https://doi.org/10.1038/s41558-018-0358-8

Gargiulo, J.I., Eastwood, C.R., Garcia, S.C., Lyons, N.A., 2018. Dairy farmers with larger herd sizes adopt more precision dairy technologies. J. Dairy Sci. 101, 5466–5473. https://doi.org/10.3168/jds.2017-13324

Gerber, P., Hristov, A.N., Henderson, B., Makkar, H., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Dijkstra, J., Oosting, S., 2013a. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. Animal 7 Suppl 2, 220–234. https://doi.org/10.1017/S1751731113000876

Gerber, P., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013b. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities.

Gerber, P., Vellinga, T., Opio, C., Steinfeld, H., 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livest. Sci. 139, 100–108. https://doi.org/10.1016/j.livsci.2011.03.012

Gourley, C.J.P., Powell, J.M., Dougherty, W.J., Weaver, D.M., 2007. Nutrient budgeting as an approach to improving nutrient management on Australian dairy farms, in: Australian Journal of Experimental Agriculture. pp. 1064–1074. https://doi.org/10.1071/EA07017

Gunn, K.M., Holly, M.A., Veith, T.L., Buda, A.R., Prasad, R., Alan Rotz, C., Soder, K.J., Stoner, A.M.K., 2019. Projected heat stress challenges and abatement opportunities for U.S. Milk production. PLoS One 14. https://doi.org/10.1371/journal.pone.0214665

Hansen, L.B., 2000. Consequences of selection for milk yield from a geneticist's viewpoint. J. Dairy Sci. 83, 1145–1150. https://doi.org/10.3168/jds.S0022-0302(00)74980-0

Hayek, M.N., Harwatt, H., Ripple, W.J., Mueller, N.D., 2020. The carbon opportunity cost of animal-sourced food production on land. Nat. Sustain. https://doi.org/10.1038/s41893-020-00603-4

Henderson, B., Falcucci, A., Mottet, A., Early, L., Werner, B., Steinfeld, H., Gerber, P., 2017. Marginal costs of abating greenhouse gases in the global ruminant livestock sector. Mitig. Adapt. Strateg. Glob. Chang. 22, 199–224. https://doi.org/10.1007/s11027-015-9673-9

Herrero, M., Henderson, B., Havlík, P., Thornton, P.K., Conant, R.T., Smith, P., Wirsenius, S., Hristov, A.N., Gerber, P., Gill, M., Butterbach-Bahl, K., Valin, H., Garnett, T., Stehfest, E., 2016. Greenhouse gas mitigation potentials in the livestock sector. Nat. Clim. Chang. https://doi.org/10.1038/nclimate2925

Hospido, A., Sonesson, U., 2005. The environmental impact of mastitis: A case study of dairy herds. Sci. Total Environ. 343, 71–82. https://doi.org/10.1016/j.scitotenv.2004.10.006

Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S., Adesogan, A.T., Yang, W., Lee, C., Gerber, P.J., Henderson, B., Tricarico, J.M., 2013a. SPECIAL TOPICS-Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options 1. J. Anim. Sci 91, 5045–5069. https://doi.org/10.2527/jas2013-6583

Hristov, A.N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., G, W., Dijkstra, J., Oosting, S., 2013b. Mitigation of greenhouse gas emissions in livestock production : a review of technical options for non-CO_2 emissions. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Hristov, A.N., Ott, T., Tricarico, J., Rotz, A., Waghorn, G., Adesogan, A., Dijkstra, J., Montes, F., Oh, J., Kebreab, E., Oosting, S.J., Gerber, P.J., Henderson, B., Makkar, H.P.S., Firkins, J.L., 2013c. SPECIAL TOPICS-Mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management mitigation options 1. J. Anim. Sci 91, 5095–5113. https://doi.org/10.2527/jas2013-6585

Huang, S.K., Kuo, L., Chou, K.L., 2016. The applicability of marginal abatement cost approach: A comprehensive review. J. Clean. Prod. 127, 59–71. https://doi.org/10.1016/j.jclepro.2016.04.013

IMF, 2019. World Economic Outlook (October 2019): Inflation rate, average consumer prices. [WWW Document]. URL https://www.imf.org/external/datamapper/PCPIPCH@WEO/OEMDC/ (accessed 12.1.19).

INEC, 2014. Censo Agropecuario [WWW Document]. URL http://inec.cr/censos/censo-agropecuario-2014 (accessed 10.18.19).

IPCC, 2019a. Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change,desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes interrestrial ecosystems.

IPCC, 2019b. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

IPCC, 2006. 2006 IPCC guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change, Cambridge, UK.

Jiang, H.D., Dong, K.Y., Zhang, K., Liang, Q.M., 2020. The hotspots, reference routes, and research trends of marginal abatement costs: A systematic review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.119809

Jimenez-Trujillo, J.A., Ibrahim, M., Pezo, D., Guevara-Hernandez, F., Gomez-Castro, H., Nahed-Toral, J., Pinto-Ruiz, R., 2011. Comparison of animal productivity and profitability between a silvopastoral system (Brachiaria brizantha associated with Leucaena leucocephala) and a conventional system (B. brizantha+chicken manure). Res. J. Biol. Sci. 6, 75–81. https://doi.org/10.3923/rjbsci.2011.75.81

Knapp, J.R., Laur, G.L., Vadas, P.A., Weiss, W.P., Tricarico, J.M., 2014. Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. J. Dairy Sci. https://doi.org/10.3168/jds.2013-7234

Lovarelli, D., Falcone, G., Orsi, L., Bacenetti, J., 2019. Agricultural small anaerobic digestion plants: Combining economic and environmental assessment. Biomass and Bioenergy 128. https://doi.org/10.1016/j.biombioe.2019.105302

Madalena, F.E., 2007. How sustainable are the breeding programs of the global main stream dairy breeds?-The Latin-American situation.

Mazzetto, A.M., Bishop, G., Styles, D., Arndt, C., Brook, R., Chadwick, D., 2020. Comparing the environmental efficiency of milk and beef production through life cycle assessment of interconnected cattle systems. J. Clean. Prod. 124108. https://doi.org/10.1016/j.jclepro.2020.124108

McGroddy, M.E., Lerner, A.M., Burbano, D. V., Schneider, L.C., Rudel, T.K., 2015. Carbon Stocks in Silvopastoral Systems: A Study from Four Communities in Southeastern Ecuador. Biotropica 47, 407–415. https://doi.org/10.1111/btp.12225

MINAE, IMN, 2014. TERCERA COMUNICACIÓN NACIONAL.

Misselbrook, T.H., Gilhespy, S.L., Cardenas, L.M., Williams, J., Dragosits, U., 2014. Inventory of Ammonia Emissions from UK Agriculture 2014 DEFRA Contract SCF0102.

Moran, D., Macleod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees, R., Topp, C.F.E., Moxey, A., 2011. Marginal Abatement Cost Curves for UK Agricultural Greenhouse Gas Emissions. J. Agric. Econ. 62, 93–118. https://doi.org/10.1111/j.1477-9552.2010.00268.x

MTTS, 2019. Salarios Mínimos Sector Privado Año 2019.

Muir, J.P., Tedeschi, L.O., Dubeux, J.C.B., Peters, M., Burkart, S., 2017. Enhancing food security in Latin America with forage legumes. Arch. Latinoam. deProducción Anim.

Mwakaje, A.G., 2008. Dairy farming and biogas use in Rungwe district, South-west Tanzania: A study of opportunities and constraints. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2007.04.013

Nicholson, F.A., Bhogal, A., Chadwick, D., Gill, E., Gooday, R.D., Lord, E., Misselbrook, T., Rollett, A.J., Sagoo, E., Smith, K.A., Thorman, R.E., Williams, J.R., Chambers, B.J., 2013. An enhanced software tool to support better use of manure nutrients: MANNER-NPK. Soil Use Manag. 29, 473–484. https://doi.org/10.1111/sum.12078

OECD, 2017. Agricultural Policies in Costa Rica.

Pattanayak, S.K., Mercer, D.E., Sills, E., Yang, J.-C., 2003. Taking stock of agroforestry adoption studies. Agrofor. Syst. 57, 173–186. https://doi.org/https://doi.org/10.1023/A:1024809108210

Pezo, D., Ríos, N., Ibrahim, M., Gómez, M., 2019. Silvopastoral Systems for Intensifying Cattle Production and Enhancing Forest Cover: The Case of Costa Rica Leveraging Agricultural Value Chains to Enhance Tropical Tree Cover and Ney Ríos CATIE-Centro Agronómico Tropical de Investigación y Enseñanza.

Phelan, P., Moloney, A.P., McGeough, E.J., Humphreys, J., Bertilsson, J., O’Riordan, E.G., O’Kiely, P., 2015. Forage Legumes for Grazing and Conserving in Ruminant Production Systems. CRC. Crit. Rev. Plant Sci. 34, 281–326. https://doi.org/10.1080/07352689.2014.898455

Piccioli-Cappelli, F., Calegari, F., Calamari, L., Bani, P., Minuti, A., 2019. Application of a NIR device for precision feeding in dairy farms: effect on metabolic conditions and milk production. Ital. J. Anim. Sci. 18, 754–765. https://doi.org/10.1080/1828051X.2019.1570829

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environ. Int. https://doi.org/10.1016/j.envint.2003.11.005

Ripple, W.J., Smith, P., Haberl, H., Montzka, S.A., McAlpine, C., Boucher, D.H., 2014. Ruminants, climate change and climate policy. Nat. Clim. Chang. https://doi.org/10.1038/nclimate2081

Rodriguez-Lizano, V., Montero-Vega, M., 2016. FACING A FREE TRADE AGREEMENT : MONTE CARLO ANALYSIS OF SMALL DAIRY. Int. J. Dev. Res. 06, 9644–9648.

Rodriguez-Lizano, V., Montero-vega, M., Paniagua-Molina, J., 2018. Free Trade Agreement: Impacts on the Costa Rican Dairy Market 12. https://doi.org/10.19041/APSTRACT/2018/1-2/11

Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T., Woznicki, S.A., 2017. Climate change and livestock: Impacts, adaptation, and mitigation. Clim. Risk Manag. https://doi.org/10.1016/j.crm.2017.02.001

Sapkota, T.B., Vetter, S.H., Jat, M.L., Sirohi, S., Shirsath, P.B., Singh, R., Jat, H.S., Smith, P., Hillier, J., Stirling, C.M., 2019. Cost-effective opportunities for climate change mitigation in Indian agriculture. Sci. Total Environ. 655, 1342–1354. https://doi.org/10.1016/j.scitotenv.2018.11.225

SEPSA, 2016. Boletín Estadístico.

Smith, P., Haberl, H., Popp, A., Erb, K.H., Lauk, C., Harper, R., Tubiello, F.N., De Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J.I., Rose, S., 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Glob. Chang. Biol. 19, 2285–2302. https://doi.org/10.1111/gcb.12160

Sova, A.D., LeBlanc, S.J., McBride, B.W., DeVries, T.J., 2014. Accuracy and precision of total mixed rations fed on commercial dairy farms. J. Dairy Sci. 97, 562–571. https://doi.org/10.3168/jds.2013-6951

Speedy, A., Sansoucy, R., 1998. Feeding Dairy Cows in the Tropics (FAO Animal Production and Health). Food & Agriculture Organisation of the United Nations.

Styles, D., Gonzalez- Mejia, A., Moorby, J., Foskolos, A., Gibbons, J., Gonzalez-Mejia, A., Moorby, J., Foskolos, A., Gibbons, J., 2018. Climate mitigation by dairy intensification depends on intensive use of spared grassland. Glob. Chang. Biol. 24, 681–693. https://doi.org/https://doi.org/10.1111/gcb.13868

Tavoni, M., Kriegler, E., Riahi, K., Van Vuuren, D.P., Aboumahboub, T., Bowen, A., Calvin, K., Campiglio, E., Kober, T., Jewell, J., Luderer, G., Marangoni, G., Mccollum, D., Van Sluisveld, M., Zimmer, A., Van Der Zwaan, B., 2015. Post-2020 climate agreements in the major economies assessed in the light of global models. Nat. Clim. Chang. 5, 119–126. https://doi.org/10.1038/nclimate2475

Tretti, A., 2019. Cost-benefit analysis of manure applications on specialized dairy farms in the highlands and lowlands of Costa Rica. CATIE.

Uwizeye, A., de Boer, I.J.M., Opio, C.I., Schulte, R.P.O., Falcucci, A., Tempio, G., Teillard, F., Casu, F., Rulli, M., Galloway, J.N., Leip, A., Erisman, J.W., Robinson, T.P., Steinfeld, H., Gerber, P.J., 2020. Nitrogen emissions along global livestock supply chains. Nat. Food 1, 437–446. https://doi.org/10.1038/s43016-020-0113-y

Van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Van Den Berg, M., Bijl, D.L., De Boer, H.S., Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., Hof, A.F., Van Sluisveld, M.A.E., 2018. Alternative pathways to the 1.5 °c target reduce the need for negative emission technologies. Nat. Clim. Chang. 8, 391–397. https://doi.org/10.1038/s41558-018-0119-8

Vargas-leitón, B., Solis-guzman, O., Sáenz-segura, F., Hidalgo, L.H., 2013. Characterization and classification of DAIRY CATTLE IN MULTIVARIATE ANALYSIS BY COSTA RICA one 24, 257–275.

Vargas-Leitón, B., Solís-Guzmán, O., Sáenz-Segura, F., León-Hidalgo, H., 2013. Caracterización y clasificación de hatos lecheros en Costa Rica mediante análisis multivariado. Agron. Mesoam. 24, 257. https://doi.org/10.15517/am.v24i2.12525

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

World Bank, 2018. World Development Indicators.

Appendix

Table A.1. Marginal Abatement Cost Curve Environmental Parameters

Name	Details	Source
Anaerobic Digestion	Methane Conversion Fraction (MCF) = 9.59% Assumed no daily spread	(IPCC, 2019b)
Ventilation & Sprinklers	Heat stress reduction increase milk yield by 7.9% for proportion of the year when heat stress is a factor.	(Fournel et al., 2017)
Precision Feeding	Assumes 2.6% increase in efficiency of daily production from a 5% reduction in variability of long particle proportion in the composition of the daily ration	(Sova et al., 2014)
Silvopastoral systems	T. *Grandis* 16.98 t CO_2e, year $^{-1}$, ha^{-1} Based on a 20% of farm area afforested.	(IPCC, 2006)
Health	Increase milk output by 7% Reduced replacement rate by 10%	(Hospido and Sonesson, 2005)
Genetic Improvement	Change to heavier, higher producing breed. Increased animal weight Milk output increased by 10% Concentrate intake increased to meet additional feed requirements	(Benchmark, 2019)

Legumes	Clover/grass mix 60% clover (Trifolium (repens)) with 50kg per ha (if application > 50kg) For extensive systems, herd sizes were kept the same, but stocking density per ha was increased. Improved grasses measure was implemented on the stocked area. Fertiliser was only applied to land utilised under the measure.	(Phelan et al., 2015)
Nutrient Management Plan	Implementation of plan resulted in an average 17% less N applied.	(Eory et al., 2015)
Improved Grasses	Minimized concentrate inputs Forage based on grasses with high proportion of dry matter digestibility For extensive systems, herd sizes were kept the same, but stocking density per ha was increased. Improved grasses measure was implemented on the stocked area. Fertiliser was only applied to land utilised under the measure.	(Speedy and Sansoucy, 1998)
Increase Concentrate	Increase amount of concentrate as single supplement by 25%	(Hristov et al., 2013c)
Manure Broadcast	Utilised Manner NPK, achieving 6% N content for slurry.	(Nicholson et al., 2013)

Table A.2. Marginal Abatement Cost Curve Cost Parameters

Name	Details	Reference
Anaerobic Digestion	Establishment and maintenance cost of anaerobic digester	(Casasola et al., 2018)
Ventilation & Sprinklers	Instalment cost and water consumption of sprinkler	(Gunn et al., 2019)
Ventilation & Sprinklers	Water rate	(ARESEP, 2017)
Precision Feeding	Tools for precision feeding	(Piccioli-Cappelli et al., 2019)

Precision Feeding	Price of software, scale indicator, and NIRS for precision feeding	Vendor information
Silvopastoral systems	Establishment and maintenance cost of silvopastoral system	(Jimenez-Trujillo et al., 2011)
Genetic Improvement	Price of Holstein cattle	Vendor information
Manure Application	Application rate of manure using different technologies	(Chen et al., 2013)
Manure Application	Contractor rate to apply manure	(Craig, 2017)
General Rates	Minimum wage of labour	(MTTS, 2019)
General Rates	Inflation rate	(IMF, 2019)

Table A.3. Participating Local Organisations

Name	Details	Link
CATIE	The Tropical Agricultural Research and Higher Education Centre	https://catie.ac.cr/
INTA	National Institute of Innovation and Transfer in Agricultural Technology	https://www.inta.go.cr/
MAG	Ministry of Agriculture Costa Rica	http://www.mag.go.cr/
UNA	National University of Costa Rica	https://www.una.ac.cr/
UCR	University of Costa Rica	https://www.ucr.ac.cr/
TEC	The Costa Rica Institute of Technology	https://www.tec.ac.cr/
UTN	National Technical University	https://www.utn.ac.cr/
Dos Pinos	Dos Pinos Milk Producers Cooperative	https://www.cooperativadospinos.com/
PROLECHE	National Chamber of Milk Producers (Costa Rica)	http://www.proleche.com/
CORFOGA	Livestock Corporation	https://www.corfoga.org/
SA	Sigma Alimentos	https://www.sigma-alimentos.com/en/

Table A.4. Variable definitions and sample descriptive statistics by farm typology

	Farm typology				
Variables	DPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
Farm characteristics					
Farm Size (ha)	251.0	80.7	59.1	49.7	57.4
Farm inputs & consumption					
Urea Fertilizer (kg yr-1)	604.4	842.4	980.0	1406.4	944.1
N (NPK) (kg yr-1)	2750.4	1195.7	916.2	1477.7	1874.4
P205 (NPK) (kg yr-1)	4569.3	1879.0	3043.8	3137.5	3633.6
K20 (NPK) (kg yr-1)	12256.9	2922.4	7745.0	9004.2	10516.4
Other N Fertilisers (kg yr-1)	837.7	2519.4	1755.0	875.5	1594.8
Fuel Consumption (l yr-1)	3657.6	1856.8	2238.2	3342.0	3031.6
Electricity (Kw-h yr-1)	21260.3	7222.8	12040.2	16603.1	16112.7
Livestock outputs and herd characteristics					
Average Milk Production (L day -1)	9.3	16.0	16.7	20.7	18.2
# Milking cows	130.0	81.0	77.0	78.0	75.0
# Dry cows	49.0	27.0	21.0	17.0	18.0
# Heifers < 2 yrs	116.0	41.0	44.0	44.0	46.0
# Heifers > 2 yrs	0.0	0.0	0.0	0.0	0.0
# Male calves	0.0	1.0	0.0	0.0	0.0
# Female calves	63.0	33.0	19.0	17.0	22.0
# Steers	0.0	1.0	0.0	1.0	0.0
# Bulls	0.0	1.0	0.0	0.0	0.0
Total Liveweight Bought (kg)	2,734	2,492	4,656	1,864	3,600
Total Liveweight Sold (kg)	6,370	1,2784	7,671	1,0159	8,411

**DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands

Table A.5. Summary of assumptions considered by expert panel

	Parameters	Unit	Base line	TM AD	TM V&S	TM PF	TM SP	EF AH	EF GI	BF IC	PM LM	PM IGV	PM NMP	MMBC
DP_E_L	**urea_fertiliser_use**	kg per ha	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	0.61	2.41
	other_n_fertiliser_use	kg per ha	14.3	11.01	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	6.1	14.09
	grass_utilisation	t per ha per year	3.72	3.72	3.8	3.82	4.64	3.29	3.72	3.67	2.7	3.27	3.72	3.72
	stocking_rate	# per ha	1.14	1.14	1.14	1.14	1.42	1.1	1.14	1.14	1.14	3.3	1.14	1.14
	total_n_animals	#	285.4	285.4	285.4	285.4	285.4	277.3	285.4	285.4	285.4	285.4	285.4	285.4
	Milk yield	litres per day	9.26	9.26	10.25	10.46	9.26	9.93	10.18	11.91	9.26	9.26	9.26	9.26
SD_E_L	**urea_fertiliser_use**	kg per ha	10.43	10.43	10.43	10.43	10.43	10.43	10.43	10.43	9.24	10.43	6.30	10.43
	other_n_fertiliser_use	kg per ha	46.01	41.57	46.01	46.01	46.01	46.01	46.01	46.01	40.76	46.01	19.32	45.67
	grass_utilisation	t per ha	5.32	5.32	5.48	5.51	6.65	4.65	5.32	5.10	4.19	5.68	5.32	5.32
	stocking_rate	# per ha	1.89	1.89	1.89	1.89	2.36	1.85	1.89	1.89	1.89	3.75	1.89	1.89
	total_n_animals	#	152.3	152.3	152.3	152.3	152.3	149.4	152.3	152.3	152.3	152.3	152.3	152.3
	Milk yield	litres per day	16.01	16.01	17.0	17.21	16.01	17.17	17.61	19.58	16.01	16.01	16.01	16.01
SD_I_L	**urea_fertiliser_use**	kg per ha	16.57	16.57	16.57	16.57	16.57	16.57	16.57	16.57	13.42	16.57	16.57	16.57
	other_n_fertiliser_use	kg per ha	45.18	40.53	45.18	45.18	45.18	45.18	45.18	45.18	36.58	45.18	44.70	44.77
	grass_utilisation	t per ha	5.81	5.81	6.01	6.05	7.26	5.02	5.81	5.45	4.50	6.37	5.81	5.81

	stocking_rate	# per ha	2.31	2.31	2.31	2.31	2.88	2.25	2.31	2.31	2.31	2.31	2.31	2.31
	total_n_animals	#	136.40	136.4	136.4	136.4	136.4	133.32	136.4	136.4	136.4	136.4	136.4	136.4
	Milk yield	litres per day	16.75	16.75	17.74	17.95	16.75	17.96	18.42	21.46	16.75	16.75	16.75	16.75
SD_I_U	**urea_fertiliser_use**	kg per ha	28.28	28.28	28.28	28.28	0.00	28.28	28.28	28.28	18.7	28.28	28.28	28.28
	other_n_fertiliser_use	kg per ha	47.32	38.41	47.32	47.32	0.00	47.32	47.32	47.32	31.30	47.32	46.95	47.01
	grass_utilisation	t per ha	6.25	6.25	6.49	6.54	7.81	5.33	6.25	5.47	4.82	7.54	6.25	6.25
	stocking_rate	# per ha	2.69	2.69	2.69	2.69	3.36	2.62	2.69	2.69	2.69	2.69	2.69	2.69
	total_n_animals	#	133.6	133.6	133.6	133.6	133.6	130.52	133.6	133.6	133.6	133.6	133.6	133.6
	Milk yield	litres per day	20.72	20.72	21.71	21.92	20.72	22.22	22.79	26.73	20.72	20.72	20.72	20.72
SD_SI_U	**urea_fertiliser_use**	kg per ha	16.46	16.46	16.46	16.46	16.46	16.46	16.46	16.46	10.70	16.46	16.46	16.46
	other_n_fertiliser_use	kg per ha	60.48	50.68	60.48	60.48	60.48	60.48	60.48	60.48	39.30	60.48	60.17	60.21
	grass_utilisation	t per ha	5.5	5.5	5.7	5.74	6.87	4.71	5.5	5.12	4.25	6.4	5.5	5.5
	stocking_rate	# per ha	2.34	2.34	2.34	2.34	2.92	2.28	2.34	2.34	2.34	2.34	2.34	2.34
	total_n_animals	#	134.0	134.0	134.0	134.0	134.0	130.78	134.0	134.0	134.0	134.0	134.0	134.0
	Milk yield	litres per day	18.18	18.18	19.17	19.38	18.18	19.49	19.99	23.48	18.18	18.18	18.18	18.18

*Typology Key: SD_E_L = Specialised Dairy Extensive Lowland; SD_I_L = Specialised Dairy Intensive Lowland; SD_SI_U = Specialised Dairy Semi-Intensive Uplands; SD_I_U = Specialised Dairy Intensive Uplands; DP_E_L = Dual-purpose Extensive Lowlands.

*Measures Key: *TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure; MM= Manure Measure

Total Word Count: ~~11211~~10934

Marginal Abatement Cost Curves for Latin American Dairy Production: A Costa Rica case study

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Abstract

This study utilises data collected from Costa Rican dairy farmers to conduct a cradle to farm gate Life Cycle Assessment and the first Marginal Abatement Cost Curve (MACC) for dairy production in Latin America. Ninety dairy farms across five farm typologies were assessed, reflecting Costa Rica's diverse agroclimatic zones and varying degrees of dairy/beef specialisation. The efficacy and cost-effectiveness of specific mitigation measures depend on farm typology, but several promising technologies are identified that increase efficiency whilst substantially reducing emissions across most farms – in particular, measures that improve animal health and increase pasture quality. Pasture measures are synergistic with silvopastoral practises and are highly effective at emission mitigation, although relatively expensive. The replacement of lower quality by-product feeds with high quality concentrate feed is a cost-effective mitigation measure at farm level, but emission reductions could be negated by indirect land use change outside the scope of the MACC analyses. Achieving carbon neutrality at farm level is not likely to be possible for most farms, with the exception of extensive farm typologies. Not all measures are suitable in every context, and additional policy support will be needed to offset financial and technical challenges related to adoption. Results of this first tropical dairy MACC study are constrained by lack of high-resolution data, but they highlight the need for farm-typology-specific mitigation recommendations. Overall, there is a high potential for pasture improvement and silvopastoral measures to mitigate the globally significant contribution of Latin American livestock production to climate change.

Keywords: MACC; LCA; milk; footprint; climate mitigation

1. Introduction

The livestock sector accounts for ~~12~~ 14.5% of all anthropogenic greenhouse gas (GHG) emissions that drive climate change ~~(FAO, 2020; Frank et al., 2019; Gerber et al., 2013b)~~(Gerber et al., 2013b). The main emissions from livestock production are methane (CH_4) from enteric fermentation and manure management (Rojas-Downing et al., 2017), and nitrous oxide (N_2O) from urine and dung deposition by grazing livestock, and manure management ~~(Gerber et al., 2013a)~~(Gerber et al., 2013a). In addition, applications of manure and synthetic fertilizer make up a sizeable proportion of N_2O emissions (Uwizeye et al., 2020). Land use change is a major global carbon dioxide (CO_2) emission source linked to livestock production (Gerber et al., 2013b), given livestock's large land footprint (Hayek et al., 2020). ~~It is widely accepted that efforts to reduce livestock emissions are crucial to global climate stabilisation efforts (Eory et al., 2018; Frank et al., 2019; UNFCCC, 2015).~~It is widely accepted that efforts to reduce livestock emissions are crucial to global climate stabilisation efforts (Frank et al., 2019). There are substantial opportunities for mitigation within livestock production systems (Smith et al., 2013), but significant investment is needed to realise these opportunities, especially in developing regions such as the Latin American and Caribbean (LAC) region ~~(Herrero et al., 2016)~~(Herrero et al., 2016). Livestock production in LAC countries accounts for 1.9 gigatons CO_2e annually (FAO, 2020). Costa Rica is an exemplar of the challenges facing livestock systems in the LAC region because: (i) its diverse agroecosystems are representative of the wider LAC region; (ii) its agriculture sector is under increasing economic pressure to consolidate; (iii) a relatively developed research infrastructure facilitates detailed analyses of emission mitigation opportunities; (iv) its government has pledged to become carbon neutral (Flagg, 2018). The objective of this paper is to develop Marginal Abatement Cost Curves (MACC) to assess the feasibility of selected GHG mitigation measures for Costa Rican dairy farmers and illustrate the economic and technological feasibility of mitigation action across the wider LAC livestock sector.

1.1 Country Context

Costa Rica has both tropical and subtropical climates, with a dry season lasting from December to April, and a wet season from May to November (Central Intelligence Agency, 2019). Dairy production occurs in the cooler highlands and the warmer lowlands (MINAE and IMN, 2014). Agriculture contributes 5% to gross domestic product (GDP) in Costa Rica (World Bank, 2018), and accounts for 31-37% of national exports (OECD, 2017). The dairy subsector produced 1.2 million litres of milk in 2017, an increase of 16% since 2011 (FAO, 2017), and dairy products account for approximately 12% of value-added in the agriculture sector (SEPSA, 2016). Over 730,000 farms in Costa Rica are classed as dairy or dual-purpose (dairy and beef) (INEC, 2014), of which 48% are small producers (fewer than 15 animals) ~~(INEC, 2014; Rodriguez-Lizano et al., 2018)~~(Rodriguez-Lizano et al., 2018). Import tariffs of up to 66% on milk products and farm cooperatives maintain high milk prices nationally (OECD, 2017). Dos Pinos, the largest cooperative, accounts for almost 88% of sales value from Costa Rican dairy farms (Rodriguez-Lizano et al., 2018). Emissions of N_2O and CH_4 from agriculture make up almost 17% of Costa Rica's anthropogenic GHG emissions (MINAE and IMN, 2014).

The phasing out of tariffs as part of the DR-CAFTA (Dominican Republic – Central American Free Trade Agreement) will lower the overall price of milk, leaving small Costa Rican dairy farmers vulnerable. ~~Recent research suggests that Costa Rican national production would decrease by up to 26% (Rodriguez-lizano et al., 2018), with the demand gap being filled by imported milk.~~Recent research suggests that Costa Rican national production would decrease by up to 26% (Rodriguez-Lizano et al., 2018), with the demand gap being filled by imported milk. As Costa Rican dairy farmers strive to remain competitive in this economic environment, it is important that mitigation measures to reduce their environmental footprint also increase efficiency, and do not place undue economic hardship on small producers who will struggle to compete with larger domestic producers and imports (Rodriguez-Lizano and Montero-Vega, 2016). For Costa Rica's carbon neutrality target, pathways to a zero-carbon economy by 2050 are being mapped ~~(André and Valenciano-Salazar, 2020; CRG, 2018).~~(CRG, 2018). The national decarbonisation plan (CRG, 2018) envisages the promotion of circular economy livestock farming and the implementation of a biodigester program. Further, the plan also anticipates the implementation of low-carbon technologies for the majority of livestock producers by 2030. However, specific plans are still required.

1.2 Marginal Abatement Cost Curves for Mitigation Measures

A MACC for GHG emissions ranks mitigation measures according to their total cost (to the farmer) per kg of CO$_2$e abated~~ (Eory et al., 2013; Moran *et al*, 2011), providing an evidence base for policymakers and producers to make informed decisions with regards to mitigation options while increasing both the quality and quantity of their product (Huang et al., 2016; Ibrahim and Kennedy, 2016; Jiang et al., 2020). ~~(Moran et al., 2011), providing an evidence base for policymakers, in terms of target setting and policy implementation (Huang et al., 2016), and producers to make informed decisions with regards to mitigation options (Jiang et al., 2020). Eory et al (2018) claims that the development of agricultural MACCs is to both visualise "low hanging fruit", in terms of agricultural GHG mitigation opportunity, and to stimulate coherent discussion around the complex issues involved in agricultural emissions reduction.

Together with integrated assessment models (IAMs), the MACC is one of the major approaches utilised in the estimation of the economic impact of climate change mitigation ~~(Clarke et al., 2014; Jiang et al., 2020).~~(Clarke et al., 2014). IAMs are utilised to investigate implications of achieving climate mitigation goals (Van Vuuren et al., 2018), providing key information for policy makers and feeding into scientific reviews (Tavoni et al., 2015) such as the Intergovernmental Panel on Climate Change (IPCC) reports (Clarke et al., 2014). IAMs generate global longer term scenarios for regions or countries that can be used to inform policy (Tavoni et al., 2015), projecting emissions trajectories and economic implications of, *inter alia*, energy and land-use transitions (Clarke et al., 2014). Important assumptions are then made in relation to population and economic growth, available resources, technological change and mitigation policy (Clarke et al., 2014). By way of comparison, MACCs can assist policy makers in the development of a portfolio of mitigation technologies applicable at a variety of scales (e.g. national, regional, sectoral, farm), assisting in both macro- and micro- level decision making (Jiang et al., 2020). In this way, MACCs and IAMs represent complementary, rather than competing, decision support tools for policy makers.

MACC studies by Crijns-Graus (2004), and more recently Ahmed et al (2020), have investigated the implementation of mitigation measures on the global livestock sector towards 2050, with a focus on the main GHG sources and measures such as improved feed digestibility and improved nutrient and grassland management. The cost-effectiveness of mitigation measures and the level of adoption vary considerably across regions (Ahmed et al., 2020). Potential adoption is predicted to be low in developing countries (Crijns-Graus et al., 2004). Promising GHG mitigation measures for tropical systems that warrant further investigation in a MACC context include pasture restoration to enhance carbon sequestration and avoid deforestation (de Oliveira Silva et al., 2015), increasing green fodder and concentrate feeding, and anaerobic digestion of cattle manure (Sapkota et al., 2019). Whilst MACCs have been produced for agricultural sectors across several countries, such as the UK, Ireland, France, New Zealand, and China (Eory et al., 2018), as far as the authors are aware, no MACC has yet been published for LAC dairy systems. The aim of this paper is to fill that gap.

In summary, Costa Rican dairy farmers exemplify the challenges faced by LAC livestock systems to contribute towards climate stabilisation objectives, with declining economic margins in an increasingly competitive global market. This study employs data mining, stakeholder consultation and life cycle assessment (LCA) to parameterise a MACC for distinct dairy farm typologies in Costa Rica. The objective is to provide new evidence on the efficacy and economic efficiency of potential GHG mitigation measures for tropical and subtropical dairy systems.

2. Methods

2. 1 Overview

Despite relatively well-developed research infrastructure there is a paucity of published Costa Rican data for some aspects of costing and abatement potentials required for a MACC. Therefore, in-country experts were consulted to supplement data shortfalls. A list of potential mitigation measures was established after a review of the literature and consultation with key expert stakeholders in multiple meetings and workshops (see tables A.1, A.2, & A.3 for sources). Farm-level activity and financial data for these measures were collected through farm surveys. The efficacy of the measures at farm level was quantified based on parameters from the literature and following IPCC (2006) good practice guidelines for GHG accounting. Efficacy was expressed in relation to fat and protein corrected milk (FPCM) output, using LCA. Cost-effectiveness of each measure was then calculated based on net costs of implementation in relation to one kg FPCM (Gerber et al., 2011), and each kg of CO_2e abated.

2.2 Studied Farms

Farm data were collected by The Tropical Agricultural Research and Higher Education Centre (CATIE) for 95 specialised dairy farms in Costa Rica in two stages. The first stage sampled 45 farms in the provinces of Alajuela, Cartago, and San José between July and December of 2018 (Fig. 1). The second stage sampled 51 farms in the provinces of Limón, Guanacaste and Alajuela between March and May 2019. The semi-structured survey was conducted via face-to-face by technical specialists utilising the open source KoBoToolbox data collection tool. After cleaning and validation data for ninety farms was used in the study (n=90).

Figure 1. **The Costa Rican study area including the six survey regions of Alajuela, Guanacaste, San José, Cartago & Limón**

The surveyed farms were classified into five typologies defined by Vargas-Leitón et al (2013) based on analysis of 1086 dairy producers supplying Dos Pinos, Costa Rica's largest dairy cooperative. Defining parameters were altitude, stocking rate, percentage of specialised breeds, amount of concentrate for milking cows and total milk production (Vargas-Leitón et al., 2013). Variable definitions and sample descriptive statistics pertinent to the farm LCA are summarised in Table A.4 The typologies are: (i) Specialised Dairy Extensive in the Lowland (SD_E_L) (35%), (ii) Specialised Dairy Intensive Lowland (SD_I_L) (22%), (iii) Specialised Dairy Semi-Intensive in the Uplands (SD_SI_U) (18%), (iv) Specialised Dairy Intensive in the Uplands (SD_I_U) (20%), and (v) Dual-purpose Extensive in the Lowlands (DP_E_L) (5%). The baseline farms were established using mean values for farm characteristics to establish the "average farm" in each farm typology.

Variables in the dataset included farm characteristics (e.g. farm area), farm inputs and consumption, and livestock outputs and herd composition. Farm inputs and consumption include annual fertiliser use in kilogrammes (kg) (urea, NPK, and other sources of N), electricity (kWh) and fuel consumption (L) and purchased animals (kg live weight). Livestock outputs and herd characteristics include average milk yield per cow in litres per day, the total number of animals in each herd cohort, and the live weight (kg) of animals sold.

2.3 Selection of appropriate mitigation measures

To select appropriate and feasible mitigation measures for the farm typologies a series of workshops and interviews were organised with experts to establish applicability, efficacy, on-farm costs and likely uptake. Workshops took place in September 2019 and January 2020 in San José and Cartago and included researchers, farm advisors and farmer groups, industry representatives, and policymakers (Table A.3). An in-situ panel of experts also specifically assessed cost, abatement potential, off-farm land sparing and overall fit for each typology. The shortlist of environmental measures selected for detailed MACC analysis is presented in Table

1. Measures are categorised into sub-groups, representing: technical measures (TM), efficiency measures (EF), pasture measures (PM), and manure measures (MM). Further detail on sources for abatement potential and cost are provided in tables A.1 and A.2.

Table 1. Mitigation measures shortlisted for evaluation in the Marginal Abatement Cost Curve

Name	Summary	Abbreviation
Anaerobic Digestion	Cost based on the CATIE system. Flares methane but does not convert to electricity	TM AD
Ventilation & Sprinklers	Heat stress reduction increases milk yield in hot periods	TM VS
Precision Feeding	Increased milk production with reduced crude protein fed	TM PF
Silvopastoral System	Based on a 20% of farm area afforested.	TM SP
Animal Health	Increase of milk production and reduced replacement rate	EF AH
Genetic Improvement	Increased milk output per cow	EF GI
Increase Concentrate	Increase amount of concentrate as single supplement by 25%	EF IC
Legumes	Increased crude protein in grazing, reduced concentrate, and reduced fertiliser application	PM LM
Improved Grasses	Forage based on grasses with higher yield and dry matter digestibility, reduced concentrate	PM IGV
Nutrient Management Plan	Reduction in nutrient application	PM NMP
Manure broadcast	Use of animal manure for forage production	MM BC

*TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure; MM= Manure Measure

2.4 Technical measures

The anaerobic digestion measure assumes that all excreta and effluent produced by housing animals (during milking and during adverse weather) is stored in the collection tank or digester bag. Costs related to the installation and management of the anaerobic digester were based upon reported costs from a commercial installation at CATIE (Casasola et al., 2018). The associated costs are related to small affordable anaerobic digesters, which flare methane, but do not include energy generation.

The ventilation and sprinkler measure assumes a reduction in heat stress during the dry season, increasing milk yield by 7.9% (Fournel et al., 2017). Costs for installation, management and water consumption were based on Gunn et al (2019). The precision feeding measure assumes a 2.6% increase in daily production from a 5% reduction in the long particle proportion of the daily ration (Sova et al., 2014). Costs for establishment and maintenance of precision feeding equipment are based on research by Piccioli-Cappelli et al (2019) and vendor information. For silvopastoral system establishment we assume that 20% of the farm area is planted, and account for CO_2 uptake by the growing trees as well as a proportionate reduction in livestock numbers. Species selection (*T. grandis*) and cost of establishment was based on silvopastoral research conducted by Pezo et al (2019) and Jimenez-Trujillo et al (2011).

2.5 Efficiency measures

Hospido and Sonesson (2005) indicate that a reduction in the instances of mastitis can improve milk yield and reduce milk losses. We assume that vaccination and more frequent animal health checks will reduce involuntary replacement rate by 10%, validated by the panel of in-country experts (summary of key parameters assumptions in Table A.5). Costs related to improved animal health, such as vaccination and more frequent health interventions, were established based on the relationship between total health cost and milk yield using linear regression of the parameters measured in baseline farms. Genetic improvement assumes a 10% increase in milk yield, linked with more concentrate feeding to satisfy higher energy requirements, informed by in-country experts and vendor information on costs (Table A.3). Increasing concentrate feeding assumes a 25% increase in high-quality concentrate in the ration, replacing lower quality feed supplements, linked with an increased milk yield. This is based on a concentrate response curve established using linear regression of the parameters measured in baseline farms. Costs related to concentrates are based on market prices.

2.6 Pasture & nutrient measures

The legumes measure assumes a 40% grass/legume mix, with fertilizer-N application capped at 50 kg ha^{-1} yr^{-1} for all farm typologies (Phelan et al., 2015). The implementation of improved grass varieties assumes a reduction in the use of concentrates and an increase in forage dry matter digestibility (Speedy and Sansoucy, 1998). It is assumed that the successful introduction of legumes and improved pasture increases average stocking density for extensive systems (DP_E_L and SD_E_L) to that achieved by the top 20% of most densely stocked farms within each typology. However, to keep these systems comparable with baseline farms, the total herd size was kept the same, and the area utilised reduced. Costs related to the establishment of legumes and improved grass varieties were assumed to be similar to the establishment of silvopastoral systems (Jimenez-Trujillo et al., 2011), utilising general labour rates (MTTS, 2019). For extensive systems, costs were calculated for land use based on increased stocking densities. Lastly, the implementation of a nutrient management plan assumed that farms would see an average 17% reduction in fertiliser use, based on previous MACC research by Eory et al. (2015). Savings related to the implementation of a nutrient management plan were based on market prices for fertiliser.

Animals graze outdoors all year round and are housed for between 4-6 hours a day, depending on whether farms are classified as upland or lowland. Therefore, relatively little manure is collected, and is diluted with wash water from the shed and milking parlour. Thus, most of the effluent collected is lightly contaminated, low dry matter content effluent, similar to dirty water (UK) (Arndt et al., 2020) or dairy shed effluent (New Zealand). Hence, based on expert judgement, many of the manure options applied to abate emissions from housed dairy systems were considered not likely to be cost-effective for Costa Rican farms.

2.7 Calculating mitigation efficacy

An attributional LCA was applied from cradle to farm gate to calculate the carbon footprint of milk production before (Fig. 2) and after application of mitigation measures, based on an adapted version of a cattle system LCA tool by Styles et al (2018) and, more recently, Mazzetto et al (2020). LCA is the calculation of inputs, outputs and environmental impacts of a system delivering a unit of product or service, accounting for all stages of raw material extraction, production, use and disposal (Rebitzer et al., 2004). Emissions of CH_4, N_2O (direct and indirect) and CO_2 to air were estimated from relevant activity data collected in the questionnaire surveys. Estimates of upstream burdens resulting from feed production, electricity generation, diesel supply and the manufacture of synthetic fertiliser were derived from Ecoinvent (version 3.4) (Wernet et al., 2016). Enteric CH_4 and manure management CH_4 and N_2O emissions were calculated using IPCC Tier 2 equations (IPCC, 2006) and Tier 2 calculation of energy intake and Nitrogen (N) excretion according to dietary crude protein (CP) intake. Soil N_2O emissions are derived from N Pasture Range and Paddock (PRP) excretion during grazing, and the application of synthetic fertiliser and manure spreading (IPCC Tier 1). Indirect emissions of N_2O were calculated based on NH_3 emission and N-leaching factors from national inventory ~~reports~~reporting from Ireland ~~(Duffy et al., 2014; Misselbrook et al., 2014)~~(Duffy et al., 2014) and the UK (Misselbrook et al., 2014). Emissions are presented as kg of CO_2e according to 100-year global warming potentials of 1, 25 and 298 per kg of CO_2, CH_4 and N_2O emitted, respectively (IPCC, 2006).

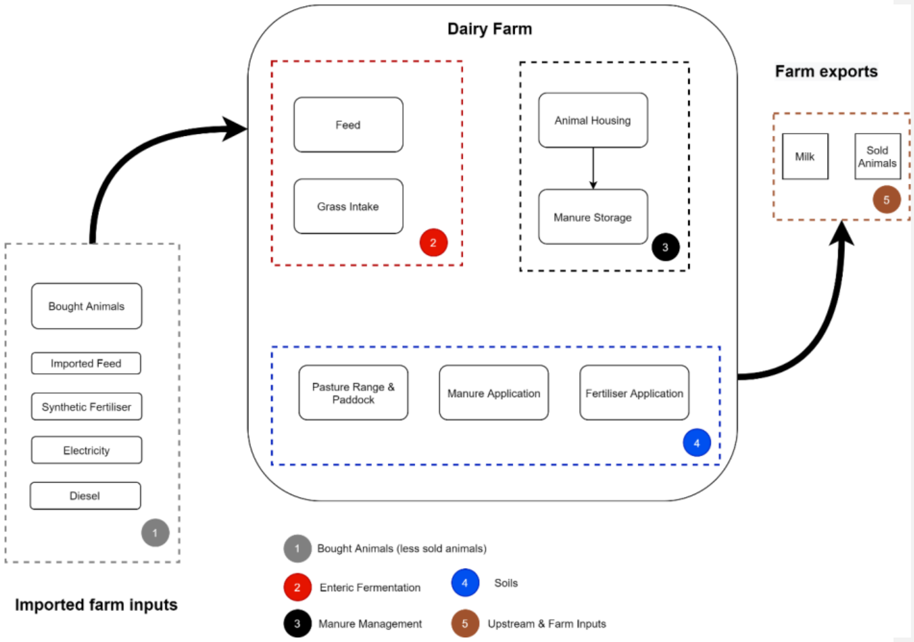


Figure 2. **System boundaries applied in the LCA, from cradle (material extraction for farm inputs) through to the farm-gate**

Calculations utilised attributional LCA to derive carbon footprints per kg of FPCM (Gerber et al., 2011) across all farms. Farm emissions were allocated to milk production (rather than animal live weight production) based on the respective gross energy content of milk and live weight exported from each farm (Mazzetto et al., 2020). Activity data and GHG emissions were averaged across farms within each farm typology to generate a baseline farm for each typology. Fig 3. presents the carbon footprint of each of the baseline farm types.

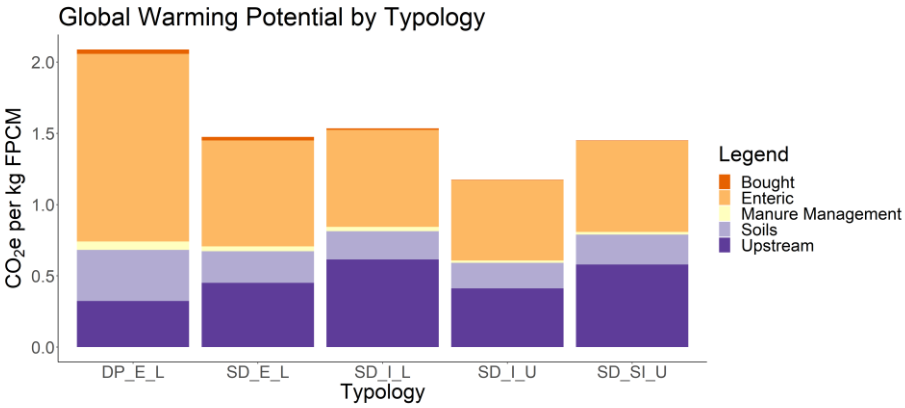


Figure 3. Average carbon footprint of milk produced across the five main dairy farm typologies, broken down by main sources: Bought-in animals, enteric methane, manure management emissions, soil emissions and emissions from upstream manufacture and transport of inputs such as fertilisers

*DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands

2.8 Costing

Net additional variable and fixed costs at the farm level were calculated for each mitigation option. Variable costs comprise inputs such as feed, fertilizer, labour, health, maintenance, transport, and services. Fixed costs comprise investment in buildings and machinery including financial costs and depreciation. The cost of investment in mitigation technologies was included in financial costs and assumed as amortisation of initial costs by the farmers (five years amortisation to install TM PF, TM SP, MM BC; fifteen years amortisation to install PM NMP). The sources for cost calculation can be found in table A.2. The base year for costs was 2019, and prior cost estimates were adjusted according to the inflation rate. The abatement cost was calculated as an increase in cost per unit of reduction in kg CO_2e from the mitigation options (based on the LCA results). The equation used to estimate abatement cost is as follows:

$$Abatement\ cost_i = \frac{Cost_i - Benefit_i}{reduced\ GHGE_i} \times -1$$

Where $Abatement\ cost_i$ is the cost of mitigation measure *i*, *Cost* is the cost of implementation, *Benefit* is the additional return received and reduced $GHGE_i$ is the expected GHG reduction.

3. Results & Discussion

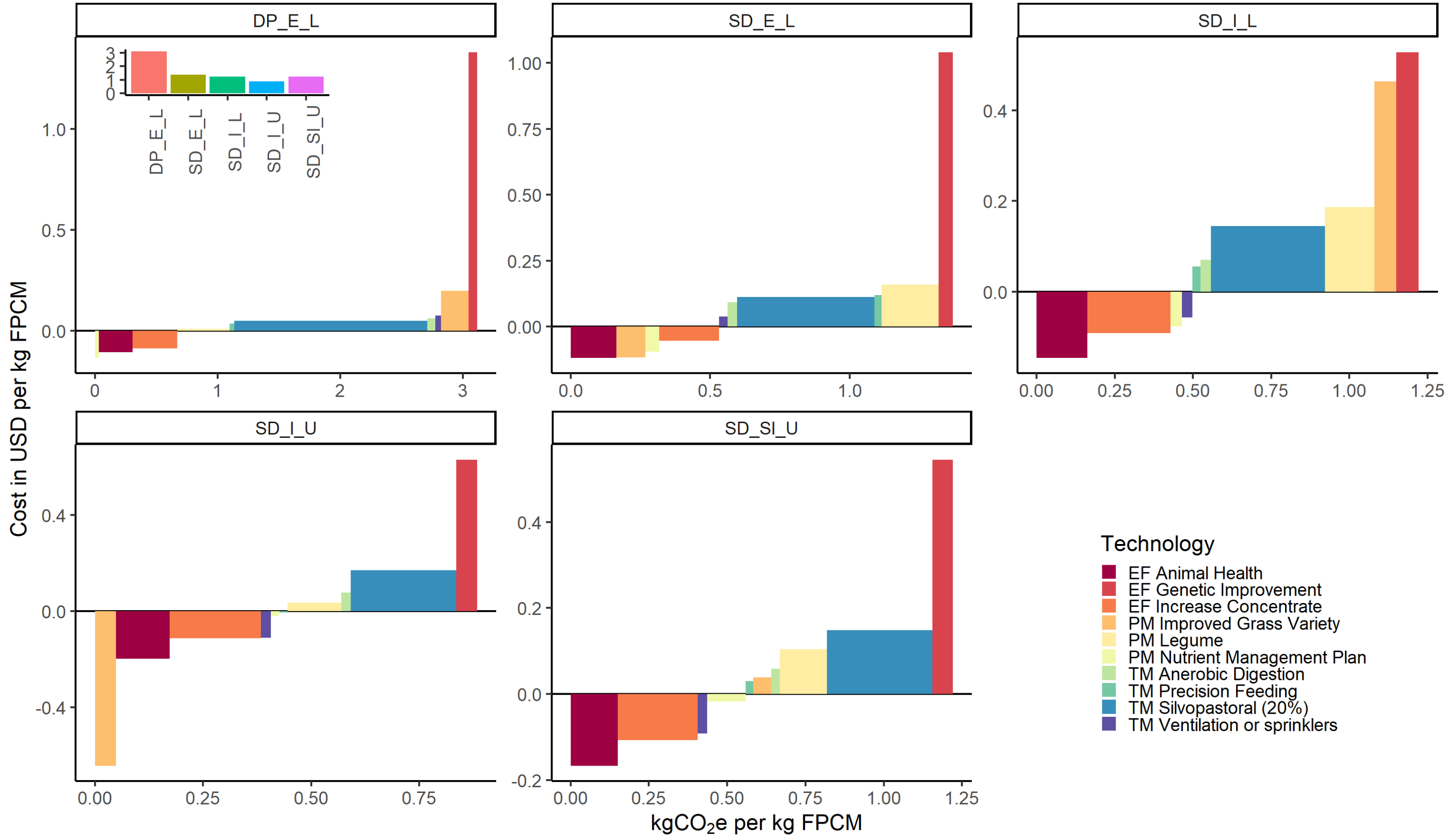
Results of the MACC are presented in Table 2 and Fig. 4 & 5, whilst Fig. 6 presents a contextual feasibility assessment of each of the mitigation measures in terms of cost, efficacy, potential for land sparing, and overall fit for each of the farm typologies. Cost and abatement potential in Fig. 6 are a direct reflection of the MACC presented in Table 2 and Fig. 4 and 5, while off-farm land sparing, and overall typology fit is based on expert opinion (Table A.3).

Table 2. Marginal Cost and kg CO_2 abatement per kg of FPCM across the assessed measures

		Typologies									
		DP_E_L		**SD_E_L**		**SD_I_L**		**SD_I_U**		**SD_SI_U**	
Code	**Measures**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**
TM AD	Anaerobic Digestion	0.06	0.07	0.09	0.03	0.07	0.03	0.08	0.02	0.06	0.03
TM V&S	Ventilation or sprinklers	0.08	0.05	0.04	0.03	-0.06	0.03	-0.11	0.02	-0.09	0.03
TM PF	Precision Feeding	0.04	0.04	0.12	0.03	0.06	0.03	-0.01	0.02	0.03	0.02
TM SP (20%)	Silvopastoral	0.05	1.57	0.11	0.49	0.14	0.36	0.17	0.24	0.15	0.34
EF AH	Animal Health	-0.11	0.27	-0.12	0.16	-0.15	0.16	-0.2	0.12	-0.17	0.15
EF GI	Genetic Improvement	1.38	0.07	1.04	0.05	0.53	0.07	0.63	0.05	0.54	0.07

EF IC	Increase Concentrate	-0.09	0.36	-0.05	0.21	-0.9	0.27	-0.11	0.21	-0.11	0.25
PM IGV	Improved Grass Variety	0.20	0.22	-0.12	0.1	0.46	0.07	-0.64	0.05	0.04	0.06
PM LM	Legume	0.01	0.43	0.16	0.2	0.19	0.16	0.04	0.12	0.1	0.15
PM NMP	Nutrient Management Plan	-0.14	0.03	-0.1	0.05	-0.08	0.04	-0.02	0.02	-0.02	0.12
MM BC	Broadcast	10.17	< 0.0	18.63	< 0.0	21.67	< 0.0	33.18	< 0.0	33.96	< 0.0

*TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure; MM= Manure Measure
**DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands
***AP =Abatement Potential kg CO_2e per kg of FPCM milk; Cost= AP Cost in $USD per kg of milk


DP_E_L
3
2
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DP_E_L
SD_E_L
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2
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SD_E_L
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0.75
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1.25
Cost in USD per kg FPCM
kgCO$_2$e per kg FPCM
Technology
EF Animal Health
EF Genetic Improvement
EF Increase Concentrate
PM Improved Grass Variety
PM Legume
PM Nutrient Management Plan
TM Anerobic Digestion
TM Precision Feeding
TM Silvopastoral (20%)
TM Ventilation or sprinklers

Figure 4. **Marginal abatement cost curve for each typology, with costs and abatement potentials related to one kg of FPCM. The top left inset graph summarises the total abatement potential per farm typology related to one kg of FPCM**

*TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure
**DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands
*** TM AD=Anaerobic Digestion; TM V&S=Ventilation or sprinklers; TM PF=Precision Feeding; TM SP (20%)=Silvopastoral; EF AH=Animal Health; EF CB=Genetic Improvement; EF IC=Increase Concentrate; PM IGV=Improved Grass Variety; PM LM=Legume; PM NMP=Nutrient Management Plan; MM BC=Broadcast

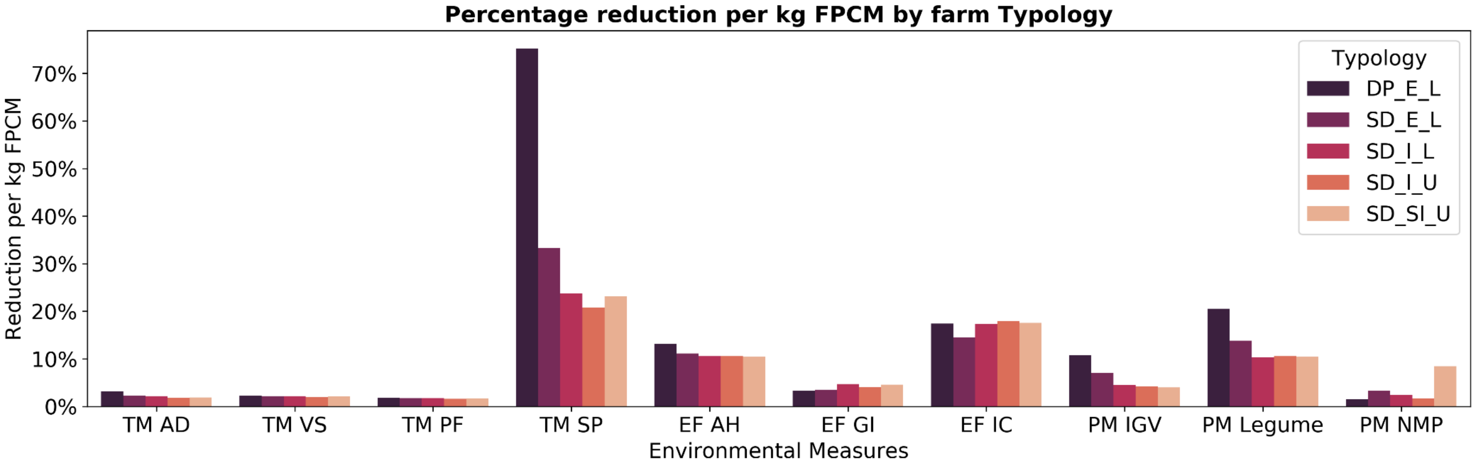

Figure 5. **Proportional abatement per kg of FPCM per mitigation measure relative to baseline emissions burden by farm typology**

*TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure
**DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands
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3.1 Technical measures

Anaerobic digestion for the production of biogas ~~has been increasing in Europe, the United States (US) and in many parts of the developing world because of the potential for sustainable energy generation alongside GHG and eutrophication mitigation (Holm-Nielsen et al., 2009; Kaparaju and Rintala, 2011).~~is recognised as an effective approach to mitigation of GHG emissions, especially when utilising waste or secondary feedstock (Bacenetti et al., 2016). However, the major challenge is the cost of implementation and technical capacity (Mwakaje, 2008). Here, anaerobic digestion implementation modestly increased costs across all farm typologies. ~~Previous studies also present a similar trend of modest additional costs to implement anaerobic digestion on farms (Moran et al., 2011; Sapkota et al., 2019).~~Previous estimates by Moran et al (2011) also present a similar trend of modest additional costs to implement anaerobic digestion on farms . Based on pricing information provided by CATIE (Casasola et al., 2018), basic *anaerobic digestion* systems can be implemented relatively cheaply in Costa Rica's warm climate. However, abatement potential was limited for all farm typologies due to the limited amount of housed manure production. Further, the diluted effluent (slurry and dirty water) has a relatively low methane yield potential. Manure-based anaerobic digestion systems typically utilise slurry, as opposed to effluent, for methane production (Lovarelli et al., 2019). Abatement potential per kg FPCM is higher for dual-purpose farms (DP_E_L) owing to their lower milk yields. Overall, quantities of house manure are not sufficient to make *anaerobic digestion* cost-effective in these tropical systems where animals mostly graze outdoors and in the absence of useful energy generation.

~~Climatic conditions that result in heat stress can have a significant impact on animal health and production (DeShazer, 2009, Fournel et al., 2017)~~Climatic conditions that result in heat stress can have a significant impact on animal health and production (Fournel et al., 2017). *Ventilation and sprinklers* are cost-effective across intensive farm typologies, reducing costs by $0.11 per kg of milk for intensive upland systems owing to increased milk yield. However, the average abatement potential is relatively low (0.03kg of CO_2e per kg of milk) and in-country experts indicated that these systems are not applicable for highland typologies. Cows in highland areas are only brought in for milking as they do not suffer heat exposure to the same degree as farms in lowland areas. Lowland farms do keep cows housed for slightly longer periods given the consistently higher temperatures experienced in these areas.

Precision Feeding is an attempt to reduce the mismatch between animal feed and the nutritional requirement of the animal (Piccioli-Cappelli et al., 2019). However, utilisation of precision feeding technologies represents a significant investment for dairy farmers (Borchers and Bewley, 2015). Here, *Precision feeding* is cost-effective only for intensive upland systems with higher output, achieving an average abatement of 0.03kg of CO_2e per kg of milk. Banhazi et al (2012) claim that current dissemination of various precision livestock technologies is fragmented and producers require additional services related to installation and maintenance of software, and the interpretation of data. Further, a study conducted by Gargiulo et al (2018) on the adoption of current precision technologies by Australian dairy farmers found that larger dairy farmers, with herd sizes exceeding 500 dairy cows, were most likely to adopt precision technologies. Given the cost and the relatively small size of dairy farms in Costa Rica, it is likely that this technology will not be feasible for most farms.

Silvopastoral systems integrate trees with livestock systems and provide benefits related to soil fertility and carbon sequestration, shade for animals, timber and non-timber products, and biodiversity benefits ~~(Dagang and Nair, 2003; McGroddy et al., 2015). The MACC results indicate a high potential for abatement, especially for extensive farms with relatively low stocking rates. Emissions are reduced by up to 70% for dual purpose farms (Fig. 5). However, the significant establishment costs (Jimenez-Trujillo et al., 2011; Pezo et al., 2019) are a barrier to adoption of silvopastoral systems (Pagiola et al., 2007). A review of agroforestry adoption studies conducted by Pattanayak et al (2003) highlighted the knowledge-intensive nature of *silvopastoral systems*, finding that the availability of extension services has a significant impact on adoption. A potential solution may entail payments for environmental services (Dinesh et al., 2015), which has seen some success in central America in the past (Pagiola et al., 2007; Porras et al., 2013).~~ (McGroddy et al., 2015). The MACC results indicate a high potential for abatement, especially for extensive farms with relatively low stocking rates. Emissions are reduced by up to 70% for dual purpose farms (Fig. 5). However, the significant establishment costs are a barrier to adoption of silvopastoral systems (Pezo et al., 2019). A review of agroforestry adoption studies conducted by Pattanayak et al (2003) highlighted the knowledge-intensive nature of *silvopastoral systems*, finding that the availability of extension services has a significant impact on adoption. A potential solution may entail payments for environmental services (Dinesh et al., 2015), which have been utilised in Columbia, Costa Rica and Nicaragua in the past (Pezo et al., 2019).

3.2 Efficiency measures

~~Mastitis reduces milk yield and taints the milk produced (Hospido and Sonesson, 2005; Ingvartsen et al., 2003). In addition, lameness and calving problems are also major causes of death in the dairy industry (Hristov et al., 2013b). The *Animal Health* measure is cost-effective for all farm typologies, reducing production costs by an average of $0.15 per kg FPCM, and up to $0.20 per kg FPCM for intensive upland farms. The average abatement potential was 0.18kg of CO_2e per kg FPCM, rising to 0.27kg of CO_2e per kg FPCM for dual-purpose farms. These results demonstrate that *Animal Health* interventions and reducing the number of replacements can have a clear benefit in terms of both economic efficiency and emissions reductions across all typologies.~~

Mastitis reduces milk yield and taints the milk produced (Hospido and Sonesson, 2005). In addition, lameness and calving problems are also major causes of death in the dairy industry (Hristov et al., 2013c). The *Animal Health* measure is cost-effective for all farm typologies, reducing production costs by an average of $0.15 per kg FPCM, and up to $0.20 per kg FPCM for intensive upland farms. The average abatement potential was 0.18kg of CO_2e per kg FPCM, rising to 0.27kg of CO_2e per kg FPCM for dual-purpose farms. These results demonstrate that *Animal Health* interventions and reducing the number of replacements can have a clear benefit in terms of both economic efficiency and emissions reductions across all typologies.

Genetic Improvement to increase milk yield has resulted in high performing~~, heavier, dairy cows (Hansen, 2000; Hristov et al., 2013b). However, these cows have different nutritional requirements and a significant up-front capital investment (Hristov et al., 2013b).~~(Hansen, 2000), heavier, dairy cows (Hristov et al., 2013c). However, these cows have different nutritional requirements (Hristov et al., 2013c) and a significant up-front capital investment. In addition, high yielding breeds may represent a significant risk to the farmer if the necessary nutrition, health and physical environment requirements cannot be met ~~(Hristov et al., 2013b; Madalena, 2007).~~(Madalena, 2007). The expected rapid gains in production often fall short of expectation (Hristov et al., 2013c). These new results show that, for Costa Rican dairy farmers, *Genetic improvement* is cost-prohibitive across all typologies, costing up to $1.38 per kg FPCM for dual-purpose farms (Table 2). For other farm typologies, the costs ranged from $1.04 to

\$0.53 per kg of milk. Average abatement potential of 0.06kg of CO_2e per kg FPCM is small relative to the cost. Furthermore, research by Madalena (2007) indicates that the potential health problems associated with these breeds are more pronounced in hotter regions. So, lowland farms in Costa Rica would struggle to provide the conditions necessary for improved breeds to achieve their genetic potential. Further research is therefore required regarding the optimal cattle breeds for Costa Rica diverse agroclimatic conditions.

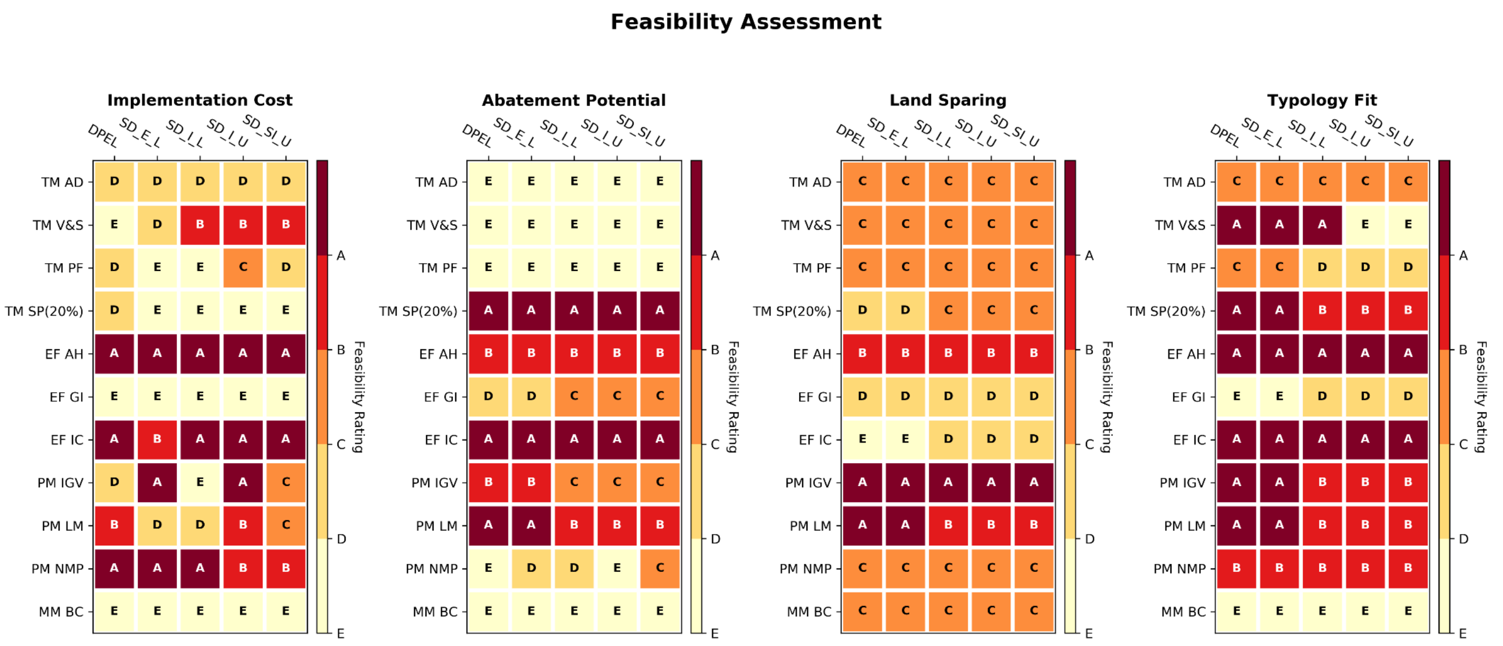
Increasing Concentrate proportions where forage quality is low has previously been shown to decrease CH_4 emissions ~~(Gerber et al., 2013a; Hristov et al., 2013b). High-quality (more energy-dense or more digestible) diets provide more energy for production and increase animal performance, lowering CH_4 emissions (Knapp et al., 2014; Muñoz et al., 2015). Similar to findings reported by (Sapkota et al., 2019), these new MACC results indicate that the increased cost of providing greater quantities of imported high-quality concentrate is offset by increased animal-level productivity across all farm typologies. On average, increasing the proportion of concentrate in the diet by 25% decreased costs by \$0.09 per kg of milk through increased yields per cow (Table 2). In terms of abatement potential, emissions were reduced by an average of 0.26 kg of CO_2e per kg FPCM. However, the increase in efficiency at animal- and farm-level comes at a cost of off-farm cropland requirement (Ripple et al., 2014; Rojas-Downing et al., 2017) (Fig. 6). Recent studies have shown that reducing milk footprints via intensification can increase emissions elsewhere via indirect land-use change to supply additional concentrate feed and via reduced dairy-beef output (Mazzetto et al., 2020; Soteriades et al., 2019; Styles et al., 2018; Vellinga and de Vries, 2018).~~(Gerber et al., 2013a). High-quality (more energy-dense or more digestible) diets provide more energy for production and increase animal performance, lowering CH_4 emissions (Hristov et al., 2013b) Further, the inclusion of high quality concentrate can, potentially, lower emissions in and of itself (Knapp et al., 2014). These MACC results indicate that the increased cost of providing greater quantities of imported high-quality concentrate is offset by increased animal-level productivity across all farm typologies. On average, increasing the proportion of concentrate in the diet by 25% decreased costs by \$0.09 per kg of milk through increased yields per cow (Table 2). In terms of abatement potential, emissions were reduced by an average of 0.26 kg of CO_2e per kg FPCM. However, the increase in efficiency at animal- and farm-level comes at a cost of off-farm cropland requirement with potential food security implications (Ripple et al., 2014) (Fig. 6). Recent studies in Costa Rica by Mazzetto et al (2020) and the UK by Styles et al (2018) have shown that reducing milk footprints via intensification can increase emissions elsewhere via indirect land-use change to supply additional concentrate feed and via reduced dairy-beef output. Results on concentrate feed must therefore be interpreted very cautiously owing to the constrained scope of MACC analyses.

3.3 Pasture & nutrient supply measures

Improved Grass Varieties and *Legumes* in pasture management have significant abatement potential and apply to all farm typologies (Table 2; Fig. 4 & 5). Henderson et al (2017) previously highlighted the abatement potential of grassland management and legume utilisation in the LAC region, whilst increasing animal productivity through forage improvement has been demonstrated as one of the most effective mitigation strategies available to dairy producers ~~(Gerber et al., 2013a)~~(Gerber et al., 2013a). The MACC indicated that the average abatement potential of *pasture legumes* (0.21 kg of CO_2e per kg of milk) is twice that of the *Improved Grass Variety* measure. However, establishing legume pastures increased cost for all typologies, by \$0.10 per kg FPCM on average, and switching to *Improved Grass Varieties* was cost-prohibitive for dual-purpose and intensive lowland farms – but decreased costs for other typologies by an average of $0.24 per kg FPCM (Table 2). The conservative modelling approach adopted in this study may under-represent improvements in milk yield associated with better quality forage ~~(Hristov et al., 2013a)~~(Hristov et al., 2013a). In addition, the potential to increase stocking density can result in spared land that can be utilised for additional income generation and/or mitigation action. Further, both measures are likely to reduce the need for concentrate usage, offsetting the financial penalty of both measures, and reducing the risk of indirect land-use change impacts associated with concentrate production (Fig. 6). However, barriers to adoption of pasture legumes by farmers will need to be overcome. These challenges include a lack of legume persistence under heavy grazing, low availability and cost of commercial seed, and a lack of farmer knowledge and training (Muir et al., 2017).

Implementation of *Nutrient Management Planning* requires an assessment of the overall farm nutrient status and assessment of the application, nutrient inventory and crop requirements. Based on this information, management options and optimum application of nutrients are calculated (Beegle et al., 2000). Evidence suggests that the introduction of nutrient budgeting tools can reduce nutrient application inefficiencies and associated costs and environmental burdens (Gourley et al., 2007). The current MACC analysis highlights a potential saving for farmers from the associated reduction in fertiliser. *Nutrient management planning* is cost-effective for all farm typologies (Table 2), especially extensive farm typologies, and achieves abatement of between 0.12 and 0.02kg of CO_2e per kg FPCM (Fig. 3). Widespread adoption of nutrient management planning may require additional extension or consulting services that could increase the costs for farmers, potentially reducing uptake (Beegle et al., 2000). In terms of overall fit, this measure could still lead to significant abatement and a reduction in costs for the farmer.

In Costa Rica, urine and faeces captured whilst animals are housed for feeding and milking are combined with water from the milking parlour and stable. These dilute effluents, known as “purines”, are then allowed to drain into the fields (Tretti, 2019). Although the cost of the basic infrastructure necessary to implement *Broadcast Manure* application to fields is low, the quantity of effluent produced by animals housed between 4-6 hours a day is too small to make this measure cost-effective for any of the typologies (Table 2). In addition, the GHG abatement potential associated with this measure is very low (Fig. 4). However, other impacts such as eutrophication may be reduced, which could justify implementation of this measure from a wider environmental protection perspective.



Feasibility Assessment

Implementation Cost

	DPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	D	D	D	D	D
TM V&S	E	D	B	B	B
TM PF	D	E	E	C	D
TM SP(20%)	D	E	E	E	E
EF AH	A	A	A	A	A
EF GI	E	E	E	E	E
EF IC	A	B	A	A	A
PM IGV	D	A	E	A	C
PM LM	B	D	D	B	C
PM NMP	A	A	A	B	B
MM BC	E	E	E	E	E

Abatement Potential

	DPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	E	E	E	E	E
TM V&S	E	E	E	E	E
TM PF	E	E	E	E	E
TM SP(20%)	A	A	A	A	A
EF AH	B	B	B	B	B
EF GI	D	D	C	C	C
EF IC	A	A	A	A	A
PM IGV	B	B	C	C	C
PM LM	A	A	B	B	B
PM NMP	E	D	D	E	C
MM BC	E	E	E	E	E

Land Sparing

	DPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	C	C	C	C	C
TM V&S	C	C	C	C	C
TM PF	C	C	C	C	C
TM SP(20%)	D	D	C	C	C
EF AH	B	B	B	B	B
EF GI	D	D	D	D	D
EF IC	E	E	D	D	D
PM IGV	A	A	A	A	A
PM LM	A	A	B	B	B
PM NMP	C	C	C	C	C
MM BC	C	C	C	C	C

Typology Fit

	DPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	C	C	C	C	C
TM V&S	A	A	A	E	E
TM PF	C	C	D	D	D
TM SP(20%)	A	A	B	B	B
EF AH	A	A	A	A	A
EF GI	E	E	D	D	D
EF IC	A	A	A	A	A
PM IGV	A	A	B	B	B
PM LM	A	A	B	B	B
PM NMP	B	B	B	B	B
MM BC	E	E	E	E	E

Figure 6. **Contextual feasibility framework for the assessment of environmental measure fit to farm typology**

*A = Very Suitable; B = Suitable; C = Somewhat Suitable; D = Somewhat Unsuitable; E = Not Suitable at all
**TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure
***DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands
**** TM AD=Anaerobic Digestion; TM V&S=Ventilation or sprinklers; TM PF=Precision Feeding; TM SP (20%)=Silvopastoral; EF AH=Animal Health; EF CB=Genetic Improvement; EF IC=Increase Concentrate; PM IGV=Improved Grass Variety; PM LM=Legume; PM NMP=Nutrient Management Plan; MM BC=Broadcast

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3.4 Looking Forward

Effective strategies for mitigation are highly context-specific. Diversity among dairy farms in Costa Rica reflects differing agroclimatic zones and degrees of dairy/beef specialisation. Mitigation options must be assessed for individual typologies. From the feasibility assessment, it is evident that there is no universal mitigation practice (Fig. 6). Results from the MACC must also take into consideration the potential co-benefits that may arise. For example, the implementation of legumes and improved pasture on more extensive farm typologies will likely leave spared land for additional income generation/mitigation activities. The utilisation of this land for synergistic mitigation measures, such as silvopastoral measures, can reduce the overall emissions burden.

Some cost-effective mitigation measures may need to be treated with caution. For example, the replacement of lower quality co-products with high quality concentrate feed. Emissions reductions may be negated by indirect land use change driven by increased crop demand, which is beyond the scope of this MACC. We strongly recommend that MACC analyses are adapted to capture important indirect consequences of farm changes, for example using a consequential (rather than attributional) LCA approach to calculate net emission savings (Styles et al., 2018).

Finally, as can be seen from the results and the contextual feasibility assessment, dairy farmers in most typologies are unlikely to achieve carbon neutrality at the farm level, with the notable exception of dual-purpose farms. However, this does not mean that farm emissions should not be significantly reduced. Many of the measures here, with further investigation and supportive policy, can increase efficiency, reduce costs and mitigate emissions. Considering that Costa Rican dairy farmers face an uncertain future, increasing farm economic and environmental sustainability is a priority. To reach carbon neutrality at a national level, a much wider view of interconnected production systems must be taken (Mazzetto et al., 2020), and other opportunities within the agriculture and land use sector, and downstream sectors, must be found to reduce and offset emissions. Significant potential exists to improve efficiency and eliminate waste from production to final consumption. The IPCC (2019a) reported that food waste alone accounts for up to 10% of global anthropogenic GHG emissions.

Recommendations for research and policy

The key research and policy recommendations arising from the results of this work are summarised below:

Improving animal health is a clear win-win measure that reduces costs and GHG emissions; a farmer awareness campaign highlighting economic savings of healthy animals, e.g. via extension services, could drive deployment of this mitigation measure.

Apparent cost and emission savings arising from replacement of by-products with concentrate feeds goes against the principle of circularity (unless higher-value uses can be found for by-products) and risks driving indirect land use change. In light of these risks, no policy recommendations can be made on this measure until further research validates animal-performance and quantifies indirect effects of crop system expansion.

Dilute purines (slurry & effluent) and short housing times mean that anaerobic digestion and efficient manure spreading technologies are not cost-effective GHG mitigation options in Costa Rica. However, the potential water quality impact arising from the current practise of draining purines into fields warrants further research to determine whether specific mitigation measures are required.

The introduction of forage legumes and silvopastoral practises could drive considerable GHG mitigation, to the point of farm-level carbon neutrality for extensive dual-purpose systems. However, based on limited available data, implementation costs appear high. Cost-effective integration of legume forages and silvopastoral practises should be a priority for future research and policy.

Reaching carbon neutrality may not always desirable at farm level. Policies and management practises should be based on holistic evidence including farm- and product-level emissions and removals (e.g. this MACC study), alongside land use efficiency and aforementioned indirect consequences of changes on inter-connected beef and cropping systems.

4. Conclusion

Costa Rica faces the twin challenges of becoming carbon neutral by 2050 and the impact on dairy farmers from the reduction of tariffs on dairy imports. Local dairy producers must reduce their emissions and remain competitive in an increasingly challenging market. Utilising primary data to establish baseline farms and a combination of literature review and expert judgement to assess mitigation potential, this study represents the first dairy farm MACC for any LAC country.

Several promising technologies can increase efficiency for farmers whilst reducing emissions. Measures that improve animal health and increase pasture quality are highlighted as particularly effective. Pasture improvement (incorporation of legumes or improved grass varieties) presents significant synergistic potential with silvopastoral practises that are highly effective at reducing net emissions, especially for extensive farm typologies. The replacement of lower quality co-product feeds with high quality concentrate feed appears to be an effective mitigation measure at the farm level, but this could be negated by indirect land use change which was outside the scope of the MACC methodology. We recommend further analyses be undertaken with a broader system boundary to consider inter-system consequences of mitigation options, in particular on interconnected beef and cropping systems.

Achieving carbon neutrality at farm level is not likely to be possible for most farm typologies, with the exception of dual-purpose farms. But many measures that improve efficiency could spare land and facilitate carbon offsetting needed to achieve carbon neutrality at national level. Not all measures are suitable in every context, and several promising measures would need additional policy support to be widely deployed, including financial and technical assistance at farm level. Overall, there is high potential for pasture improvement and silvopastoral measures to mitigate the contribution of livestock production in LAC to climate change.

Declaration

The authors confirm that this study has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Declaration of Interest

None.

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References

Ahmed, J., Almeida, E., Aminetzah, D., Denis, N., Henderson, K., Katz, J., Kitchel, H., Mannion, P., 2020. Agriculture and climate change reducing emissions through improved farming practices.

~~André, F.J., Valenciano-Salazar, J.A., 2020. Becoming carbon neutral in Costa Rica to be more sustainable: An AHP approach. Sustain. 12. https://doi.org/10.3390/su12020737~~

ARESEP, 2017. Pliegos tarifarios del servisio de acueducto, AyA 2017-2021 [WWW Document]. URL https://aresep.go.cr/tarifas/tarifas-vigentes/2199-tarifa-acueducto-aya-2017-2021 (accessed 12.6.19).

Arndt, C., Misselbrook, T.H., Vega, A., Gonzalez-Quintero, R., Chavarro-Lobo, J.A., Mazzetto, A.M., Chadwick, D.R., 2020. Measured ammonia emissions from tropical and subtropical pastures: A comparison with 2006 IPCC, 2019 Refinement to the 2006 IPCC, and EMEP/EEA (European Monitoring and Evaluation Programme and European Environmental Agency) inventory estimates. J. Dairy Sci. 103, 6706–6715. https://doi.org/10.3168/jds.2019-17825

Bacenetti, J., Sala, C., Fusi, A., Fiala, M., 2016. Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable. Appl. Energy 179, 669–686. https://doi.org/10.1016/j.apenergy.2016.07.029

Banhazi, T.M., Babinszky, L., Halas, V., Tscharke, M., 2012. Precision livestock farming: Precision feeding technologies and sustainable livestock production. Int. J. Agric. Biol. Eng. https://doi.org/10.3965/j.ijabe.20120504.006

Beegle, D.B., Carton, O.T., Bailey, J.S., 2000. Nutrient Management Planning: Justification, Theory, Practice.

Benchmark, 2019. The Cattle Site [WWW Document]. URL http://thecattlesite.com/ (accessed 11.6.19).

Borchers, M.R., Bewley, J.M., 2015. An assessment of producer precision dairy farming technology use, prepurchase considerations, and usefulness. J. Dairy Sci. 98, 4198–4205. https://doi.org/10.3168/jds.2014-8963

Casasola, F., Villanueva, C., Ibrahim, M., Lombo, D., 2018. Tecnologías relevantes para la gestión integral del estiércol en fincas ganaderas de Costa Rica. Turrialba, Costa Rica, CATIE.

Central Intelligence Agency, 2019. Costa Rica Fact Summary. World Fact B. 1.

Chen, L., de Haro Marti, M., Gray, W., Neibling, H., Chahine, M., Yadanaparthi, S., 2013. On-Farm Comparison of Two Liquid Dairy Manure Application Methods in Terms of Ammonia Emission, Odor Emission, and Costs [WWW Document]. URL https://lpelc.org/on-farm-comparison-of-two-liquid-dairy-manure-application-methods-in-terms-of-ammonia-emission-odor-emission-and-costs/ (accessed 9.28.19).

Clarke, L.K., Jiang, K., Akimoto, M., Babiker, G., Blanford, K., Fisher-Vanden, J.C., Hourcade, V., Krey, E., Kriegler, A., Löschel, D., McCollum, S., Paltsev, S., Rose, P.R., Shukla, M., Tavoni, B.C., van der Zwaan, C., van Vuuren, D.P., 2014. Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Craig, K., 2017. The Farm Management Handbook 2017/18. SAC Consulting, Edinburgh.

CRG, 2018. Decarbonization Plan Government of Costa Rica Decarbonization Plan Commitment of the Bicentennial Government.

Crijns-Graus, W.H.J., Harmelink, M., Hendriks, C., 2004. Marginal greenhouse gas abatement curves for agriculture. Utrecht.

~~Dagang, A.B.K., Nair, P.K.R., 2003. Silvopastoral research and adoption in Central America: recent findings and recommendations for future directions.~~

de Oliveira Silva, R., Barioni, L.G., Albertini, T.Z., Eory, V., Topp, C.F.E., Fernandes, F.A., Moran, D., 2015. Developing a nationally appropriate mitigation measure from the greenhouse gas GHG abatement potential from livestock production in the Brazilian Cerrado. Agric. Syst. 140, 48–55. https://doi.org/10.1016/j.agsy.2015.08.011

~~DeShazer, J.A., 2009. Livestock energetics and thermal environmental management. American Society of Agricultural and Biological Engineers.~~

Dinesh, D., Frid-Nielsen, S., Norman, J., Mutamba, M., Maria, A., Rodriguez, Loboguerrero Campbell, B., 2015. Is Climate-Smart Agriculture effective? A review of selected cases.

Duffy, P., Hanley, E., Hyde, B., O'brien, P., Ponzi, J., Cotter, E., Black, K., 2014. Ireland national inventory report 2012 greenhouse gas emissions 1990-2010 reported to the united nations framework convention on climate change. Wexford, Ireland.

Eory, V., MacLeod, M., Topp, C.F.E., Rees, R.M., Webb, J., McVittie, A., Wall, E., Borthwick, F., Watson, C., Waterhouse, A., others, 2015. Review and update the UK Agriculture Marginal Abatement Cost Curve to assess the greenhouse gas abatement potential for the 5th carbon budget period and to 2050. Assess Abat. Potential 5th Carbon Final Rep. Submitt. Proj. Contract "Provision Serv. to Rev. Updat. UK Agric. MACC toBudget Period to 2050.

Eory, V., Pellerin, S., Carmona Garcia, G., Lehtonen, H., Licite, I., Mattila, H., Lund-Sørensen, T., Muldowney, J., Popluga, D., Strandmark, L., Schulte, R., 2018. Marginal abatement cost curves for agricultural climate policy: State-of-the art, lessons learnt and future potential. J. Clean. Prod. 182, 705–716. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.01.252

~~Eory, V., Topp, C.F.E., Moran, D., 2013. Multiple-pollutant cost-effectiveness of greenhouse gas mitigation measures in the UK agriculture. Environ. Sci. Policy 27, 55–67. https://doi.org/10.1016/j.envsci.2012.11.003~~

FAO, 2020. Transforming the livestock sector through the Sustainable Development Goals. Rome, Italy.

FAO, 2017. FAOSTAT.

Flagg, J.A., 2018. Carbon neutral by 2021: The past and present of Costa Rica's unusual political tradition. Sustain. 10. https://doi.org/10.3390/su10020296

Fournel, S., Ouellet, V., Charbonneau, É., 2017. Practices for alleviating heat stress of dairy cows in humid continental climates: A literature review. Animals 7, 1–23. https://doi.org/10.3390/ani7050037

Frank, S., Havlík, P., Stehfest, E., van Meijl, H., Witzke, P., Pérez-Domínguez, I., van Dijk, M., Doelman, J.C., Fellmann, T., Koopman, J.F.L., Tabeau, A., Valin, H., 2019. Agricultural non-CO2 emission reduction potential in the context of the 1.5 °C target. Nat. Clim. Chang. 9, 66–72. https://doi.org/10.1038/s41558-018-0358-8

Gargiulo, J.I., Eastwood, C.R., Garcia, S.C., Lyons, N.A., 2018. Dairy farmers with larger herd sizes adopt more precision dairy technologies. J. Dairy Sci. 101, 5466–5473. https://doi.org/10.3168/jds.2017-13324

Gerber, P., Hristov, A.N., Henderson, B., Makkar, H., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Dijkstra, J., Oosting, S., 2013a. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. Animal 7 Suppl 2, 220–234. https://doi.org/10.1017/S1751731113000876

Gerber, P., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013b. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities.

Gerber, P., Vellinga, T., Opio, C., Steinfeld, H., 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livest. Sci. 139, 100–108. https://doi.org/10.1016/j.livsci.2011.03.012

Gourley, C.J.P., Powell, J.M., Dougherty, W.J., Weaver, D.M., 2007. Nutrient budgeting as an approach to improving nutrient management on Australian dairy farms, in: Australian Journal of Experimental Agriculture. pp. 1064–1074. https://doi.org/10.1071/EA07017

Gunn, K.M., Holly, M.A., Veith, T.L., Buda, A.R., Prasad, R., Alan Rotz, C., Soder, K.J., Stoner, A.M.K., 2019. Projected heat stress challenges and abatement opportunities for U.S. Milk production. PLoS One 14. https://doi.org/10.1371/journal.pone.0214665

Hansen, L.B., 2000. Consequences of selection for milk yield from a geneticist's viewpoint. J. Dairy Sci. 83, 1145–1150. https://doi.org/10.3168/jds.S0022-0302(00)74980-0

Hayek, M.N., Harwatt, H., Ripple, W.J., Mueller, N.D., 2020. The carbon opportunity cost of animal-sourced food production on land. Nat. Sustain. https://doi.org/10.1038/s41893-020-00603-4

Henderson, B., Falcucci, A., Mottet, A., Early, L., Werner, B., Steinfeld, H., Gerber, P., 2017. Marginal costs of abating greenhouse gases in the global ruminant livestock sector. Mitig. Adapt. Strateg. Glob. Chang. 22, 199–224. https://doi.org/10.1007/s11027-015-9673-9

Herrero, M., Henderson, B., Havlík, P., Thornton, P.K., Conant, R.T., Smith, P., Wirsenius, S., Hristov, A.N., Gerber, P., Gill, M., Butterbach-Bahl, K., Valin, H., Garnett, T., Stehfest, E., 2016. Greenhouse gas mitigation potentials in the livestock sector. Nat. Clim. Chang. https://doi.org/10.1038/nclimate2925

~~Holm-Nielsen, J.B., Al Seadi, T., Oleskowicz-Popiel, P., 2009. The future of anaerobic digestion and biogas utilization. Bioresour. Technol. 100, 5478–5484. https://doi.org/10.1016/j.biortech.2008.12.046~~

Hospido, A., Sonesson, U., 2005. The environmental impact of mastitis: A case study of dairy herds. Sci. Total Environ. 343, 71–82. https://doi.org/10.1016/j.scitotenv.2004.10.006

Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, ~~#~~H~~-~~.P .S~~,~~., Adesogan, ~~‖~~A~~-~~.T~~,~~., Yang, ~~¶~~W~~,~~., Lee, C., Gerber~~‖~~, P.J., Henderson~~‖~~, B., Tricarico, J.M., 2013a. SPECIAL TOPICS-Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options 1. J. Anim. Sci 91, 5045–5069. https://doi.org/10.2527/jas2013-6583

Hristov, A.N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., G, W., Dijkstra, J., Oosting, S., 2013b. Mitigation of greenhouse gas emissions in livestock production : a review of technical options for non-CO_2 emissions. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Hristov, A.N., Ott, T., Tricarico, J., Rotz, A., Waghorn, G., Adesogan, A., Dijkstra, ~~#~~J~~,~~., Montes, ~~‖~~F~~,~~., Oh, ~~¶~~J~~,~~., Kebreab, E., Oosting, S.J., Gerber, ~~‖~~P~~-~~.J~~,~~., Henderson, ~~†~~B~~,~~., Makkar, H.P.S., Firkins, J.L., ~~2013b~~2013c. SPECIAL TOPICS-Mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management mitigation options 1. J. Anim. Sci 91, 5095–5113. https://doi.org/10.2527/jas2013-6585

Huang, S.K., Kuo, L., Chou, K.L., 2016. The applicability of marginal abatement cost approach: A comprehensive review. J. Clean. Prod. 127, 59–71. https://doi.org/10.1016/j.jclepro.2016.04.013

~~Ibrahim, N., Kennedy, C., 2016. A methodology for constructing marginal abatement cost curves for climate action in cities. Energies 9. https://doi.org/10.3390/en9040227~~

IMF, 2019. World Economic Outlook (October 2019): Inflation rate, average consumer prices. [WWW Document]. URL https://www.imf.org/external/datamapper/PCPIPCH@WEO/OEMDC/ (accessed 12.1.19).

INEC, 2014. Censo Agropecuario [WWW Document]. URL http://inec.cr/censos/censo-agropecuario-2014 (accessed 10.18.19).

~~Ingvartsen, K.L., Dewhurst, R.J., Friggens, N.C., 2003. On the relationship between lactational performance and health: Is it yield or metabolic imbalance that cause production diseases in dairy cattle? A position paper, in: Livestock Production Science. Elsevier, pp. 277–308. https://doi.org/10.1016/S0301-6226(03)00110-6~~

IPCC, 2019a. Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change,desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes interrestrial ecosystems.

IPCC, 2019b. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

IPCC, 2006. 2006 IPCC guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change, Cambridge, UK.

Jiang, H.D., Dong, K.Y., Zhang, K., Liang, Q.M., 2020. The hotspots, reference routes, and research trends of marginal abatement costs: A systematic review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.119809

Jimenez-Trujillo, J.A., Ibrahim, M., Pezo, D., Guevara-Hernandez, F., Gomez-Castro, H., Nahed-Toral, J., Pinto-Ruiz, R., 2011. Comparison of animal productivity and profitability between a silvopastoral system (Brachiaria brizantha associated with Leucaena leucocephala) and a conventional system (B. brizantha+chicken manure). Res. J. Biol. Sci. 6, 75–81. https://doi.org/10.3923/rjbsci.2011.75.81

~~Kaparaju, P., Rintala, J., 2011. Mitigation of greenhouse gas emissions by adopting anaerobic digestion technology on dairy, sow and pig farms in Finland. Renew. Energy 36, 31–41. https://doi.org/10.1016/j.renene.2010.05.016~~

Knapp, J.R., Laur, G.L., Vadas, P.A., Weiss, W.P., Tricarico, J.M., 2014. Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. J. Dairy Sci. https://doi.org/10.3168/jds.2013-7234

Lovarelli, D., Falcone, G., Orsi, L., Bacenetti, J., 2019. Agricultural small anaerobic digestion plants: Combining economic and environmental assessment. Biomass and Bioenergy 128. https://doi.org/10.1016/j.biombioe.2019.105302

Madalena, F.E., 2007. How sustainable are the breeding programs of the global main stream dairy breeds?-The Latin-American situation.

Mazzetto, A.M., Bishop, G., Styles, D., Arndt, C., Brook, R., Chadwick, D., 2020. Comparing the environmental efficiency of milk and beef production through life cycle assessment of interconnected cattle systems. J. Clean. Prod. 124108. https://doi.org/10.1016/j.jclepro.2020.124108

McGroddy, M.E., Lerner, A.M., Burbano, D. V., Schneider, L.C., Rudel, T.K., 2015. Carbon Stocks in Silvopastoral Systems: A Study from Four Communities in Southeastern Ecuador. Biotropica 47, 407–415. https://doi.org/10.1111/btp.12225

MINAE, IMN, 2014. TERCERA COMUNICACIÓN NACIONAL.

Misselbrook, T.H., Gilhespy, S.L., Cardenas, L.M., Williams, J., Dragosits, U., 2014. Inventory of Ammonia Emissions from UK Agriculture 2014 DEFRA Contract SCF0102.

Moran, D., Macleod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees, R., Topp, C.F.E., Moxey, A., 2011. Marginal Abatement Cost Curves for UK Agricultural Greenhouse Gas Emissions. J. Agric. Econ. 62, 93–118. https://doi.org/10.1111/j.1477-9552.2010.00268.x

MTTS, 2019. Salarios Mínimos Sector Privado Año 2019.

Muir, J.P., Tedeschi, L.O., Dubeux, J.C.B., Peters, M., Burkart, S., 2017. Enhancing food security in Latin America with forage legumes. Arch. Latinoam. deProducción Anim.

~~Muñoz, C., Hube, S., Morales, J.M., Yan, T., Ungerfeld, E.M., 2015. Effects of concentrate supplementation on enteric methane emissions and milk production of grazing dairy cows. Livest. Sci. 175, 37–46. https://doi.org/10.1016/j.livsci.2015.02.001~~

Mwakaje, A.G., 2008. Dairy farming and biogas use in Rungwe district, South-west Tanzania: A study of opportunities and constraints. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2007.04.013

Nicholson, F.A., Bhogal, A., Chadwick, D., Gill, E., Gooday, R.D., Lord, E., Misselbrook, T., Rollett, A.J., Sagoo, E., Smith, K.A., Thorman, R.E., Williams, J.R., Chambers, B.J., 2013. An enhanced software tool to support better use of manure nutrients: MANNER-NPK. Soil Use Manag. 29, 473–484. https://doi.org/10.1111/sum.12078

OECD, 2017. Agricultural Policies in Costa Rica.

~~Pagiola, S., Ramírez, E., Gobbi, J., de Haan, C., Ibrahim, M., Murgueitio, E., Ruíz, J.P., 2007. Paying for the environmental services of silvopastoral practices in Nicaragua. Ecol. Econ. 64, 374–385. https://doi.org/10.1016/j.ecolecon.2007.04.014~~

Pattanayak, S.K., Mercer, D.E., Sills, E., Yang, J.-C., 2003. Taking stock of agroforestry adoption studies. Agrofor. Syst. 57, 173–186. https://doi.org/https://doi.org/10.1023/A:1024809108210

Pezo, D., Ríos, N., Ibrahim, M., Gómez, M., 2019. Silvopastoral Systems for Intensifying Cattle Production and Enhancing Forest Cover: The Case of Costa Rica Leveraging Agricultural Value Chains to Enhance Tropical Tree Cover and Ney Ríos CATIE-Centro Agronómico Tropical de Investigación y Enseñanza.

Phelan, P., Moloney, A.P., McGeough, E.J., Humphreys, J., Bertilsson, J., O'Riordan, E.G., O'Kiely, P., 2015. Forage Legumes for Grazing and Conserving in Ruminant Production Systems. CRC. Crit. Rev. Plant Sci. 34, 281–326. https://doi.org/10.1080/07352689.2014.898455

Piccioli-Cappelli, F., Calegari, F., Calamari, L., Bani, P., Minuti, A., 2019. Application of a NIR device for precision feeding in dairy farms: effect on metabolic conditions and milk production. Ital. J. Anim. Sci. 18, 754–765. https://doi.org/10.1080/1828051X.2019.1570829

~~Porras, I., Barton, D.N., Miranda, M., Chacón-Cascante, A., 2013. Learning from 20 years of Payments for Ecosystem Services in Costa Rica. London, UK.~~

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environ. Int. https://doi.org/10.1016/j.envint.2003.11.005

Ripple, W.J., Smith, P., Haberl, H., Montzka, S.A., McAlpine, C., Boucher, D.H., 2014. Ruminants, climate change and climate policy. Nat. Clim. Chang. https://doi.org/10.1038/nclimate2081

Rodriguez-Lizano, V., Montero-Vega, M., 2016. FACING A FREE TRADE AGREEMENT : MONTE CARLO ANALYSIS OF SMALL DAIRY. Int. J. Dev. Res. 06, 9644–9648.

Rodriguez-Lizano, V., Montero-vega, M., Paniagua-Molina, J., 2018. Free Trade Agreement: Impacts on the Costa Rican Dairy Market 12. https://doi.org/10.19041/APSTRACT/2018/1-2/11

Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T., Woznicki, S.A., 2017. Climate change and livestock: Impacts, adaptation, and mitigation. Clim. Risk Manag. https://doi.org/10.1016/j.crm.2017.02.001

Sapkota, T.B., Vetter, S.H., Jat, M.L., Sirohi, S., Shirsath, P.B., Singh, R., Jat, H.S., Smith, P., Hillier, J., Stirling, C.M., 2019. Cost-effective opportunities for climate change mitigation in Indian agriculture. Sci. Total Environ. 655, 1342–1354. https://doi.org/10.1016/j.scitotenv.2018.11.225

SEPSA, 2016. Boletín Estadístico.

Smith, P., Haberl, H., Popp, A., Erb, K.H., Lauk, C., Harper, R., Tubiello, F.N., De Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J.I., Rose, S., 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Glob. Chang. Biol. 19, 2285–2302. https://doi.org/10.1111/gcb.12160

~~Soteriades, A.D., Foskolos, A., Styles, D., Gibbons, J.M., 2019. Diversification not specialization reduces global and local environmental burdens from livestock production. Environ. Int. 132, 104837. https://doi.org/10.1016/j.envint.2019.05.031~~

Sova, A.D., LeBlanc, S.J., McBride, B.W., DeVries, T.J., 2014. Accuracy and precision of total mixed rations fed on commercial dairy farms. J. Dairy Sci. 97, 562–571. https://doi.org/10.3168/jds.2013-6951

Speedy, A., Sansoucy, R., 1998. Feeding Dairy Cows in the Tropics (FAO Animal Production and Health). Food & Agriculture Organisation of the United Nations.

Styles, D., Gonzalez- Mejia, A., Moorby, J., Foskolos, A., Gibbons, J., Gonzalez-Mejia, A., Moorby, J., Foskolos, A., Gibbons, J., 2018. Climate mitigation by dairy intensification depends on intensive use of spared grassland. Glob. Chang. Biol. 24, 681–693. https://doi.org/https://doi.org/10.1111/gcb.13868

Tavoni, M., Kriegler, E., Riahi, K., Van Vuuren, D.P., Aboumahboub, T., Bowen, A., Calvin, K., Campiglio, E., Kober, T., Jewell, J., Luderer, G., Marangoni, G., Mccollum, D., Van Sluisveld, M., Zimmer, A., Van Der Zwaan, B., 2015. Post-2020 climate agreements in the major economies assessed in the light of global models. Nat. Clim. Chang. 5, 119–126. https://doi.org/10.1038/nclimate2475

Tretti, A., 2019. Cost-benefit analysis of manure applications on specialized dairy farms in the highlands and lowlands of Costa Rica. CATIE.

~~UNFCCC, 2015. Paris Agreement on Climate Change. United Nations Framework Convention on Climate Change. https://doi.org/10.1201/9781351116589-2~~

Uwizeye, A., de Boer, I.J.M., Opio, C.I., Schulte, R.P.O., Falcucci, A., Tempio, G., Teillard, F., Casu, F., Rulli, M., Galloway, J.N., Leip, A., Erisman, J.W., Robinson, T.P., Steinfeld, H., Gerber, P.J., 2020. Nitrogen emissions along global livestock supply chains. Nat. Food 1, 437–446. https://doi.org/10.1038/s43016-020-0113-y

Van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Van Den Berg, M., Bijl, D.L., De Boer, H.S., Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., Hof, A.F., Van Sluisveld, M.A.E., 2018. Alternative pathways to the 1.5 °c target reduce the need for negative emission technologies. Nat. Clim. Chang. 8, 391–397. https://doi.org/10.1038/s41558-018-0119-8

Vargas-leitón, B., Solis-guzman, O., Sáenz-segura, F., Hidalgo, L.H., 2013. Characterization and classification of DAIRY CATTLE IN MULTIVARIATE ANALYSIS BY COSTA RICA one 24, 257–275.

Vargas-Leitón, B., Solís-Guzmán, O., Sáenz-Segura, F., León-Hidalgo, H., 2013. Caracterización y clasificación de hatos lecheros en Costa Rica mediante análisis multivariado. Agron. Mesoam. 24, 257. https://doi.org/10.15517/am.v24i2.12525

~~Vellinga, T. V., de Vries, M., 2018. Effectiveness of climate change mitigation options considering the amount of meat produced in dairy systems. Agric. Syst. 162, 136–144.~~

~~https://doi.org/10.1016/j.agsy.2018.01.026~~

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

World Bank, 2018. World Development Indicators.

Appendix

Table A.1. Marginal Abatement Cost Curve Environmental Parameters

Name	Details	Source
Anaerobic Digestion	Methane Conversion Fraction (MCF) = 9.59% Assumed no daily spread	(IPCC, 2019b)
Ventilation & Sprinklers	Heat stress reduction increase milk yield by 7.9% for proportion of the year when heat stress is a factor.	(Fournel et al., 2017)
Precision Feeding	Assumes 2.6% increase in efficiency of daily production from a 5% reduction in variability of long particle proportion in the composition of the daily ration	(Sova et al., 2014)
Silvopastoral systems	T. *Grandis* 16.98 t CO_2e, year $^{-1}$, ha^{-1} Based on a 20% of farm area afforested.	(IPCC, 2006)
Health	Increase milk output by 7% Reduced replacement rate by 10%	(Hospido and Sonesson, 2005)
Genetic Improvement	Change to heavier, higher producing breed. Increased animal weight Milk output increased by 10% Concentrate intake increased to meet additional feed requirements	(Benchmark, 2019)
Legumes	Clover/grass mix 60% clover (Trifolium (repens)) with 50kg per ha (if application > 50kg) For extensive systems, herd sizes were kept the same, but stocking density per ha was increased. Improved grasses measure was implemented on the stocked area. Fertiliser was only applied to land utilised under the measure.	(Phelan et al., 2015)

Nutrient Management Plan	Implementation of plan resulted in an average 17% less N applied.	(Eory et al., 2015)
Improved Grasses	Minimized concentrate inputs Forage based on grasses with high proportion of dry matter digestibility For extensive systems, herd sizes were kept the same, but stocking density per ha was increased. Improved grasses measure was implemented on the stocked area. Fertiliser was only applied to land utilised under the measure.	(Speedy and Sansoucy, 1998)
Increase Concentrate	Increase amount of concentrate as single supplement by 25%	~~(Hristov et al., 2013b)~~(Hristov et al., 2013c)
Manure Broadcast	Utilised Manner NPK, achieving 6% N content for slurry.	(Nicholson et al., 2013)

Table A.2. Marginal Abatement Cost Curve Cost Parameters

Name	Details	Reference
Anaerobic Digestion	Establishment and maintenance cost of anaerobic digester	(Casasola et al., 2018)
Ventilation & Sprinklers	Instalment cost and water consumption of sprinkler	(Gunn et al., 2019)
Ventilation & Sprinklers	Water rate	(ARESEP, 2017)
Precision Feeding	Tools for precision feeding	(Piccioli-Cappelli et al., 2019)
Precision Feeding	Price of software, scale indicator, and NIRS for precision feeding	Vendor information
Silvopastoral systems	Establishment and maintenance cost of silvopastoral system	(Jimenez-Trujillo et al., 2011)
Genetic Improvement	Price of Holstein cattle	Vendor information
Manure Application	Application rate of manure using different technologies	(Chen et al., 2013)
Manure Application	Contractor rate to apply manure	(Craig, 2017)

General Rates	Minimum wage of labour	(MTTS, 2019)
General Rates	Inflation rate	(IMF, 2019)

Table A.3. Participating Local Organisations

Name	**Details**	**Link**
CATIE	The Tropical Agricultural Research and Higher Education Centre	https://catie.ac.cr/
INTA	National Institute of Innovation and Transfer in Agricultural Technology	https://www.inta.go.cr/
MAG	Ministry of Agriculture Costa Rica	http://www.mag.go.cr/
UNA	National University of Costa Rica	https://www.una.ac.cr/
UCR	University of Costa Rica	https://www.ucr.ac.cr/
TEC	The Costa Rica Institute of Technology	https://www.tec.ac.cr/
UTN	National Technical University	https://www.utn.ac.cr/
Dos Pinos	Dos Pinos Milk Producers Cooperative	https://www.cooperativadospinos.com/
PROLECHE	National Chamber of Milk Producers (Costa Rica)	http://www.proleche.com/
CORFOGA	Livestock Corporation	https://www.corfoga.org/
SA	Sigma Alimentos	https://www.sigma-alimentos.com/en/

Table A.4. Variable definitions and sample descriptive statistics by farm typology

	Farm typology				
Variables	DPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
Farm characteristics					
Farm Size (ha)	251.0	80.7	59.1	49.7	57.4
Farm inputs & consumption					

Urea Fertilizer (kg yr-1)	604.4	842.4	980.0	1406.4	944.1
N (NPK) (kg yr-1)	2750.4	1195.7	916.2	1477.7	1874.4
P205 (NPK) (kg yr-1)	4569.3	1879.0	3043.8	3137.5	3633.6
K20 (NPK) (kg yr-1)	12256.9	2922.4	7745.0	9004.2	10516.4
Other N Fertilisers (kg yr-1)	837.7	2519.4	1755.0	875.5	1594.8
Fuel Consumption (l yr-1)	3657.6	1856.8	2238.2	3342.0	3031.6
Electricity (Kw-h yr-1)	21260.3	7222.8	12040.2	16603.1	16112.7
Livestock outputs and herd characteristics					
Average Milk Production (L day -1)	9.3	16.0	16.7	20.7	18.2
# Milking cows	130.0	81.0	77.0	78.0	75.0
# Dry cows	49.0	27.0	21.0	17.0	18.0
# Heifers < 2 yrs	116.0	41.0	44.0	44.0	46.0
# Heifers > 2 yrs	0.0	0.0	0.0	0.0	0.0
# Male calves	0.0	1.0	0.0	0.0	0.0
# Female calves	63.0	33.0	19.0	17.0	22.0
# Steers	0.0	1.0	0.0	1.0	0.0
# Bulls	0.0	1.0	0.0	0.0	0.0
Total Liveweight Bought (kg)	2,734	2,492	4,656	1,864	3,600
Total Liveweight Sold (kg)	6,370	1,2784	7,671	1,0159	8,411

**DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands

Table A.5. Summary of assumptions considered by expert panel

	Parameters	Unit	Base line	TM AD	TM V&S	TM PF	TM SP	EF AH	EF GI	BF IC	PM LM	PM IGV	PM NMP	MMBC

DP_E_L	**urea_fertiliser_use**	kg per ha	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	0.61	2.41
	other_n_fertiliser_use	kg per ha	14.3	11.01	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	6.1	14.09
	grass_utilisation	t per ha per year	3.72	3.72	3.8	3.82	4.64	3.29	3.72	3.67	2.7	3.27	3.72	3.72
	stocking_rate	# per ha	1.14	1.14	1.14	1.14	1.42	1.1	1.14	1.14	1.14	3.3	1.14	1.14
	total_n_animals	#	285.4	285.4	285.4	285.4	285.4	277.3	285.4	285.4	285.4	285.4	285.4	285.4
	Milk yield	litres per day	9.26	9.26	10.25	10.46	9.26	9.93	10.18	11.91	9.26	9.26	9.26	9.26
SD_E_L	**urea_fertiliser_use**	kg per ha	10.43	10.43	10.43	10.43	10.43	10.43	10.43	10.43	9.24	10.43	6.30	10.43
	other_n_fertiliser_use	kg per ha	46.01	41.57	46.01	46.01	46.01	46.01	46.01	46.01	40.76	46.01	19.32	45.67
	grass_utilisation	t per ha	5.32	5.32	5.48	5.51	6.65	4.65	5.32	5.10	4.19	5.68	5.32	5.32
	stocking_rate	# per ha	1.89	1.89	1.89	1.89	2.36	1.85	1.89	1.89	1.89	3.75	1.89	1.89
	total_n_animals	#	152.3	152.3	152.3	152.3	152.3	149.4	152.3	152.3	152.3	152.3	152.3	152.3
	Milk yield	litres per day	16.01	16.01	17.0	17.21	16.01	17.17	17.61	19.58	16.01	16.01	16.01	16.01
SD_I_L	**urea_fertiliser_use**	kg per ha	16.57	16.57	16.57	16.57	16.57	16.57	16.57	16.57	13.42	16.57	16.57	16.57
	other_n_fertiliser_use	kg per ha	45.18	40.53	45.18	45.18	45.18	45.18	45.18	45.18	36.58	45.18	44.70	44.77
	grass_utilisation	t per ha	5.81	5.81	6.01	6.05	7.26	5.02	5.81	5.45	4.50	6.37	5.81	5.81
	stocking_rate	# per ha	2.31	2.31	2.31	2.31	2.88	2.25	2.31	2.31	2.31	2.31	2.31	2.31
	total_n_animals	#	136.40	136.4	136.4	136.4	136.4	133.32	136.4	136.4	136.4	136.4	136.4	136.4
	Milk yield	litres per day	16.75	16.75	17.74	17.95	16.75	17.96	18.42	21.46	16.75	16.75	16.75	16.75

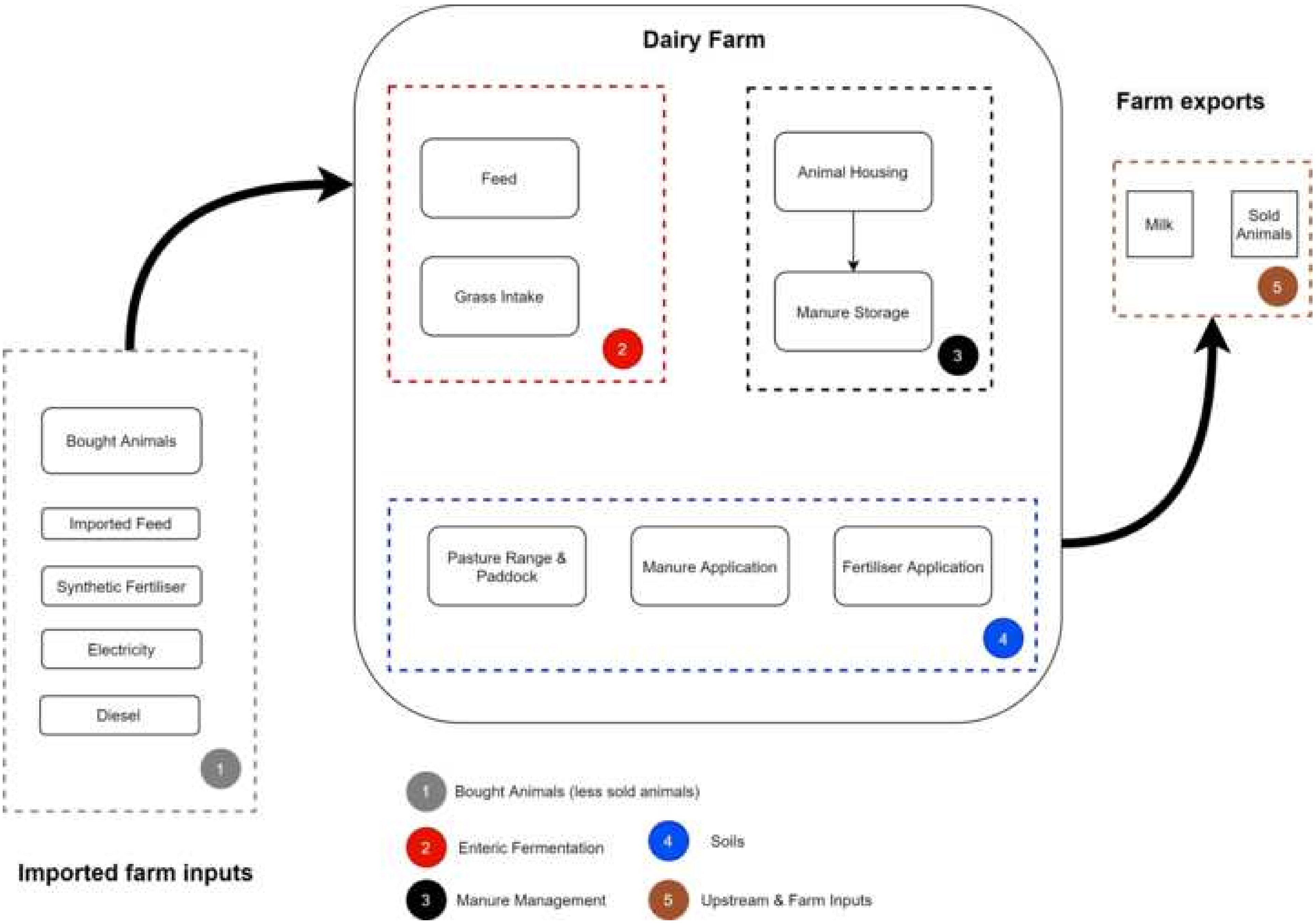
SD_I_U	**urea_fertiliser_use**	kg per ha	28.28	28.28	28.28	28.28	0.00	28.28	28.28	28.28	18.7	28.28	28.28	28.28
	other_n_fertiliser_use	kg per ha	47.32	38.41	47.32	47.32	0.00	47.32	47.32	47.32	31.30	47.32	46.95	47.01
	grass_utilisation	t per ha	6.25	6.25	6.49	6.54	7.81	5.33	6.25	5.47	4.82	7.54	6.25	6.25
	stocking_rate	# per ha	2.69	2.69	2.69	2.69	3.36	2.62	2.69	2.69	2.69	2.69	2.69	2.69
	total_n_animals	#	133.6	133.6	133.6	133.6	133.6	130.52	133.6	133.6	133.6	133.6	133.6	133.6
	Milk yield	litres per day	20.72	20.72	21.71	21.92	20.72	22.22	22.79	26.73	20.72	20.72	20.72	20.72
SD_SI_U	**urea_fertiliser_use**	kg per ha	16.46	16.46	16.46	16.46	16.46	16.46	16.46	16.46	10.70	16.46	16.46	16.46
	other_n_fertiliser_use	kg per ha	60.48	50.68	60.48	60.48	60.48	60.48	60.48	60.48	39.30	60.48	60.17	60.21
	grass_utilisation	t per ha	5.5	5.5	5.7	5.74	6.87	4.71	5.5	5.12	4.25	6.4	5.5	5.5
	stocking_rate	# per ha	2.34	2.34	2.34	2.34	2.92	2.28	2.34	2.34	2.34	2.34	2.34	2.34
	total_n_animals	#	134.0	134.0	134.0	134.0	134.0	130.78	134.0	134.0	134.0	134.0	134.0	134.0
	Milk yield	litres per day	18.18	18.18	19.17	19.38	18.18	19.49	19.99	23.48	18.18	18.18	18.18	18.18

*Typology Key: SD_E_L = Specialised Dairy Extensive Lowland; SD_I_L = Specialised Dairy Intensive Lowland; SD_SI_U = Specialised Dairy Semi-Intensive Uplands; SD_I_U = Specialised Dairy Intensive Uplands; DP_E_L = Dual-purpose Extensive Lowlands.

*Measures Key: *TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure; MM= Manure Measure

Figure_1


Alajuela
Guanacaste
Limón
Cartago
San José
Rivas
San José
Cañas
Quesada
Guápiles
Siquirres
Nicoya
San Francisco
San Vicente
Turrialba
San Jose
San Isidro
Puerto Armuelles


Dairy Farm
Feed
Grass Intake
2
Animal Housing
Manure Storage
3
Pasture Range & Paddock
Manure Application
Fertiliser Application
4
Farm exports
Milk
Sold Animals
5
Bought Animals
Imported Feed
Synthetic Fertiliser
Electricity
Diesel
1
Imported farm inputs
1 Bought Animals (less sold animals)
2 Enteric Fermentation
4 Soils
3 Manure Management
5 Upstream & Farm Inputs

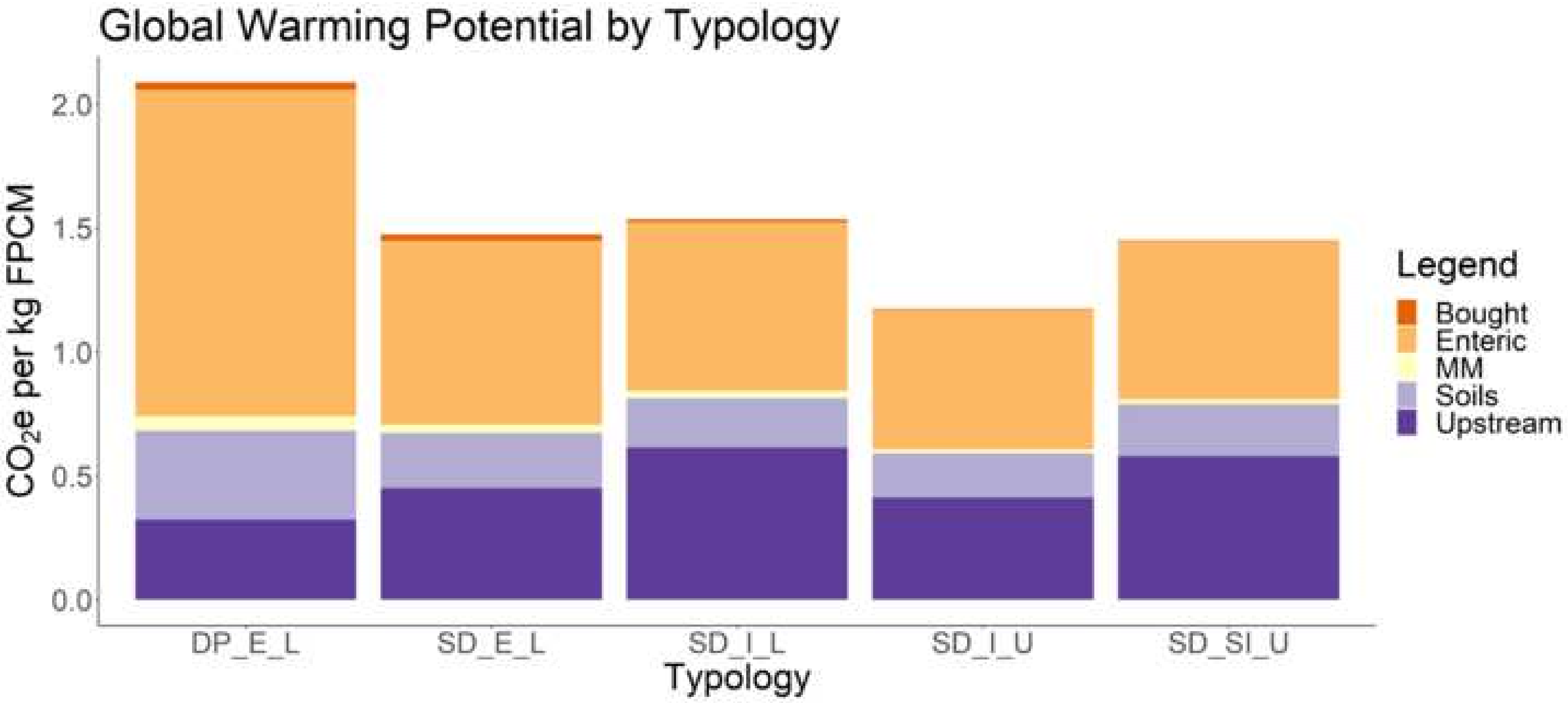
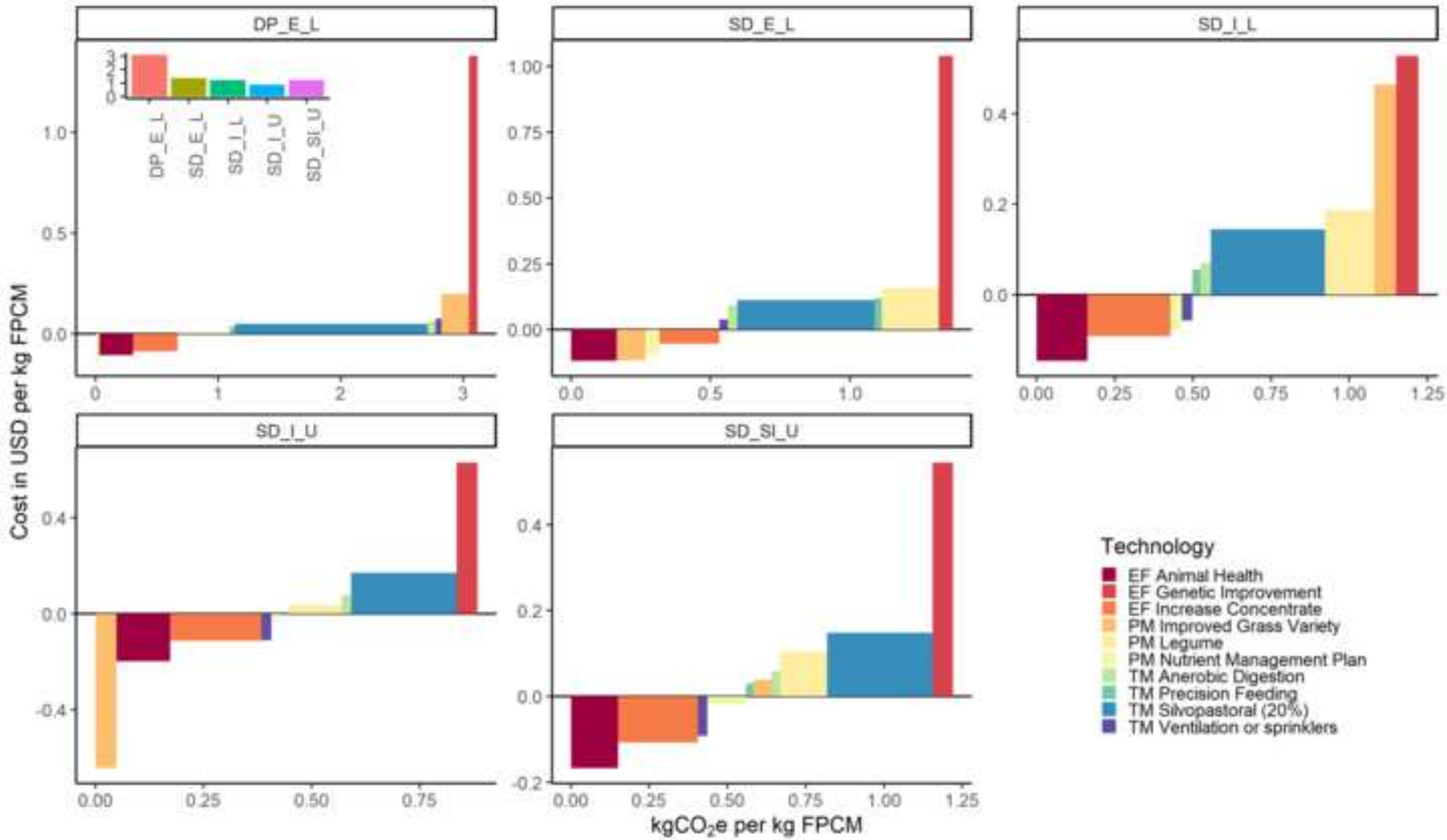
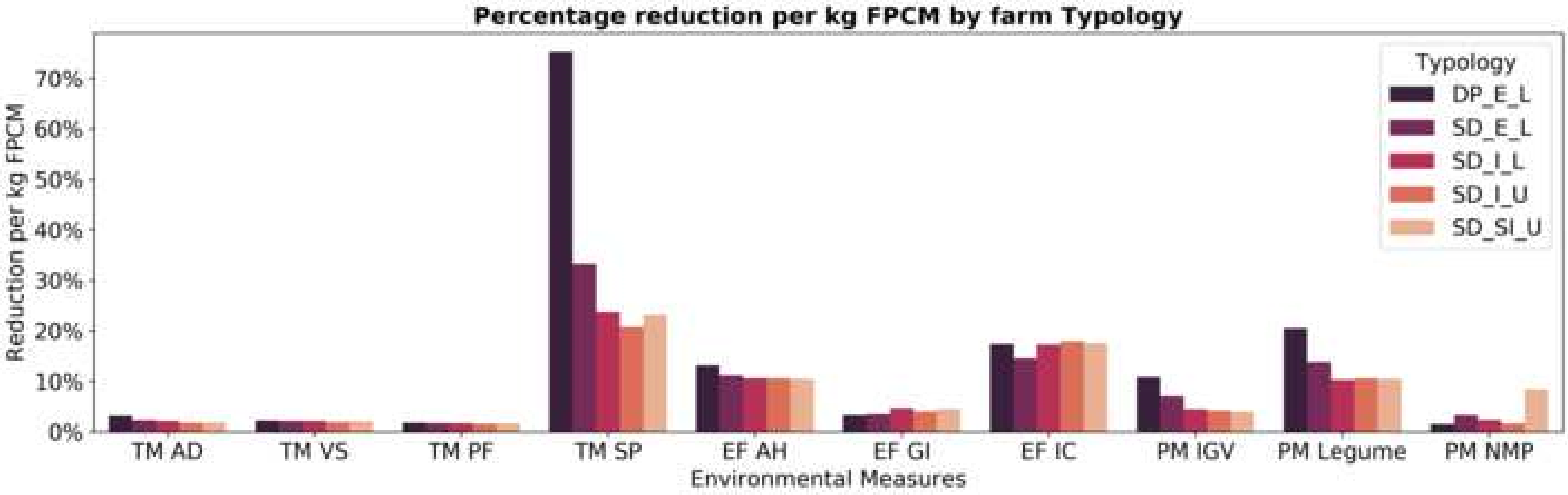
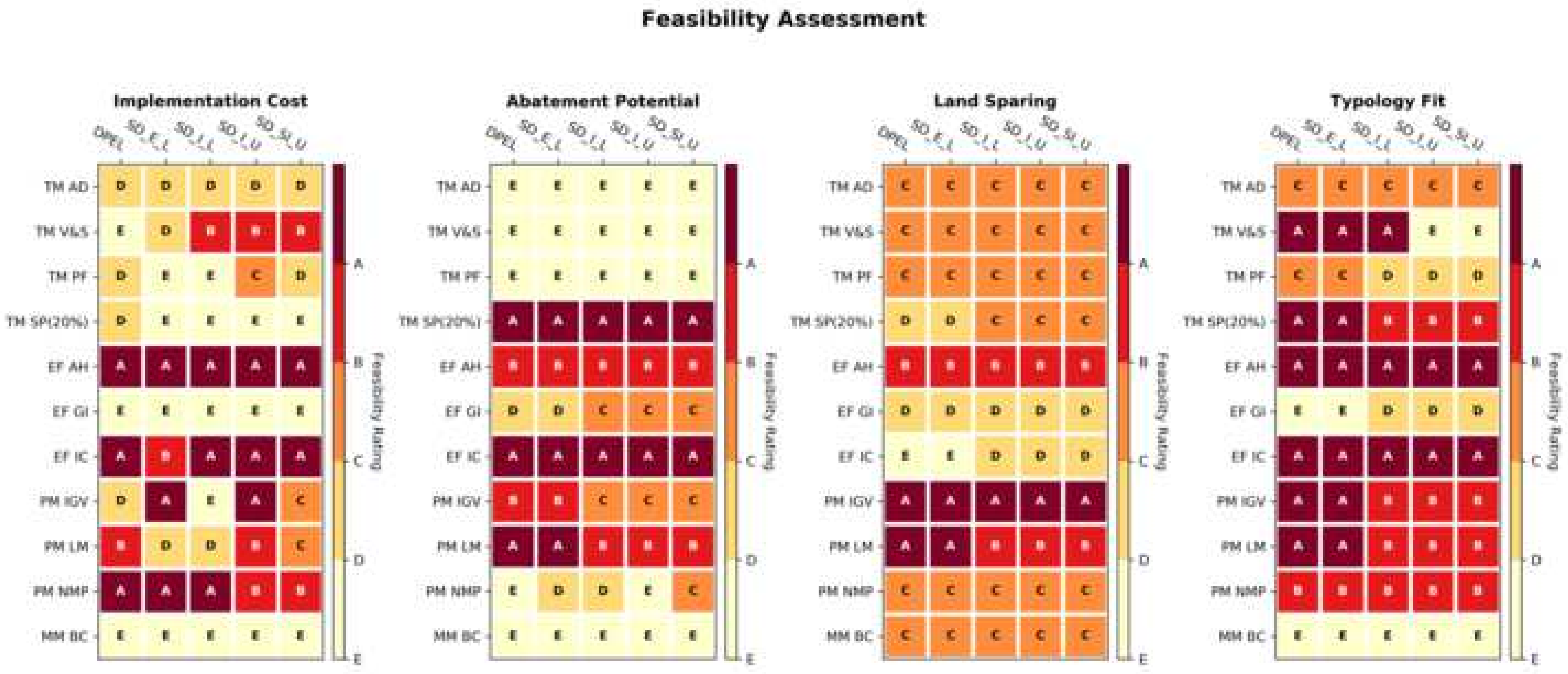

Global Warming Potential by Typology
CO$_2$e per kg FPCM
2.0
1.5
1.0
0.5
0.0
DP_E_L
SD_E_L
SD_I_L
SD_I_U
SD_SI_U
Typology
Legend
Bought
Enteric
MM
Soils
Upstream

Figure 4


DP_E_L
SD_E_L
SD_I_L
SD_I_U
SD_SI_U
Cost in USD per kg FPCM
kgCO$_2$e per kg FPCM
0
1
2
3
DP_E_L
SD_E_L
SD_I_L
SD_I_U
SD_SI_U
1.0
0.5
0.0
0
1
2
3
1.00
0.75
0.50
0.25
0.00
0.0
0.5
1.0
0.4
0.2
0.0
0.00
0.25
0.50
0.75
1.00
1.25
0.4
0.0
-0.4
0.00
0.25
0.50
0.75
0.4
0.2
0.0
-0.2
0.00
0.25
0.50
0.75
1.00
1.25
Technology
EF Animal Health
EF Genetic Improvement
EF Increase Concentrate
PM Improved Grass Variety
PM Legume
PM Nutrient Management Plan
TM Anerobic Digestion
TM Precision Feeding
TM Silvopastoral (20%)
TM Ventilation or sprinklers


Percentage reduction per kg FPCM by farm Typology
Reduction per kg FPCM
0%
10%
20%
30%
40%
50%
60%
70%
TM AD
TM VS
TM PF
TM SP
EF AH
EF GI
EF IC
PM IGV
PM Legume
PM NMP
Environmental Measures
Typology
DP_E_L
SD_E_L
SD_I_L
SD_I_U
SD_SI_U



Feasibility Assessment

Implementation Cost

	OPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	D	D	D	D	D
TM V&S	E	D	B	B	B
TM PF	D	E	E	C	D
TM SP(20%)	D	E	E	E	E
EF AH	A	A	A	A	A
EF GI	E	E	E	E	E
EF IC	A	B	A	A	A
PM IGV	D	A	E	A	C
PM LM	B	D	D	B	C
PM NMP	A	A	A	B	B
MM BC	E	E	E	E	E

Abatement Potential

	OPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	E	E	E	E	E
TM V&S	E	E	E	E	E
TM PF	E	E	E	E	E
TM SP(20%)	A	A	A	A	A
EF AH	B	B	B	B	B
EF GI	D	D	C	C	C
EF IC	A	A	A	A	A
PM IGV	B	B	C	C	C
PM LM	A	A	B	B	B
PM NMP	E	D	D	E	C
MM BC	E	E	E	E	E

Land Sparing

	OPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	C	C	C	C	C
TM V&S	C	C	C	C	C
TM PF	C	C	C	C	C
TM SP(20%)	D	D	C	C	C
EF AH	B	B	B	B	B
EF GI	D	D	D	D	D
EF IC	E	E	D	D	D
PM IGV	A	A	A	A	A
PM LM	A	A	B	B	B
PM NMP	C	C	C	C	C
MM BC	C	C	C	C	C

Typology Fit

	OPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
TM AD	C	C	C	C	C
TM V&S	A	A	A	E	E
TM PF	C	C	D	D	D
TM SP(20%)	A	A	B	B	B
EF AH	A	A	A	A	A
EF GI	E	E	D	D	D
EF IC	A	A	A	A	A
PM IGV	A	A	B	B	B
PM LM	A	A	B	B	B
PM NMP	B	B	B	B	B
MM BC	E	E	E	E	E

Table 1. Mitigation measures shortlisted for evaluation in the Marginal Abatement Cost Curve

Name	Summary	Abbreviation
Anaerobic Digestion	Cost based on the CATIE system. Flares methane but does not convert to electricity	TM AD
Ventilation & Sprinklers	Heat stress reduction increases milk yield in hot periods	TM VS
Precision Feeding	Increased milk production with reduced crude protein fed	TM PF
Silvopastoral System	Based on a 20% of farm area afforested.	TM SP
Animal Health	Increase of milk production and reduced replacement rate	EF AH
Genetic Improvement	Increased milk output per cow	EF GI
Increase Concentrate	Increase amount of concentrate as single supplement by 25%	EF IC
Legumes	Increased crude protein in grazing, reduced concentrate, and reduced fertiliser application	PM LM
Improved Grasses	Forage based on grasses with higher yield and dry matter digestibility, reduced concentrate	PM IGV
Nutrient Management Plan	Reduction in nutrient application	PM NMP
Manure broadcast	Use of animal manure for forage production	MM BC

*TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure; MM= Manure Measure

Table 2. Marginal Cost and kg CO_2 abatement per kg of FPCM across the assessed measures

		Typologies									
		DP_E_L		**SD_E_L**		**SD_I_L**		**SD_I_U**		**SD_SI_U**	
Code	**Measures**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**	**Cost ($)**	**Abatement (kg CO_2 e)**
TM AD	Anaerobic Digestion	0.06	0.07	0.09	0.03	0.07	0.03	0.08	0.02	0.06	0.03
TM V&S	Ventilation or sprinklers	0.08	0.05	0.04	0.03	-0.06	0.03	-0.11	0.02	-0.09	0.03
TM PF	Precision Feeding	0.04	0.04	0.12	0.03	0.06	0.03	-0.01	0.02	0.03	0.02
TM SP (20%)	Silvopastoral	0.05	1.57	0.11	0.49	0.14	0.36	0.17	0.24	0.15	0.34
EF AH	Animal Health	-0.11	0.27	-0.12	0.16	-0.15	0.16	-0.2	0.12	-0.17	0.15
EF GI	Genetic Improvement	1.38	0.07	1.04	0.05	0.53	0.07	0.63	0.05	0.54	0.07
EF IC	Increase Concentrate	-0.09	0.36	-0.05	0.21	-0.9	0.27	-0.11	0.21	-0.11	0.25
PM IGV	Improved Grass Variety	0.20	0.22	-0.12	0.1	0.46	0.07	-0.64	0.05	0.04	0.06
PM LM	Legume	0.01	0.43	0.16	0.2	0.19	0.16	0.04	0.12	0.1	0.15
PM NMP	Nutrient Management Plan	-0.14	0.03	-0.1	0.05	-0.08	0.04	-0.02	0.02	-0.02	0.12
MM BC	Broadcast	10.17	< 0.0	18.63	< 0.0	21.67	< 0.0	33.18	< 0.0	33.96	< 0.0

*TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure; MM= Manure Measure
**DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands
***AP =Abatement Potential kg CO_2e per kg of

Table A.1. Marginal Abatement Cost Curve Environmental Parameters

Name	Details	Source
Anaerobic Digestion	Methane Conversion Fraction (MCF) = 9.59% Assumed no daily spread	(IPCC, 2019b)
Ventilation & Sprinklers	Heat stress reduction increase milk yield by 7.9% for proportion of the year when heat stress is a factor.	(Fournel et al., 2017)
Precision Feeding	Assumes 2.6% increase in efficiency of daily production from a 5% reduction in variability of long particle proportion in the composition of the daily ration	(Sova et al., 2014)
Silvopastoral systems	T. *Grandis* 16.98 t CO_2e, year $^{-1}$, ha^{-1} Based on a 20% of farm area afforested.	(IPCC, 2006)
Health	Increase milk output by 7% Reduced replacement rate by 10%	(Hospido and Sonesson, 2005)
Genetic Improvement	Change to heavier, higher producing breed. Increased animal weight Milk output increased by 10% Concentrate intake increased to meet additional feed requirements	(Benchmark, 2019)
Legumes	Clover/grass mix 60% clover (Trifolium (repens)) with 50kg per ha (if application > 50kg) For extensive systems, herd sizes were kept the same, but stocking density per ha was increased. Improved grasses measure was implemented on the stocked area. Fertiliser was only applied to land utilised under the measure.	(Phelan et al., 2015)
Nutrient Management Plan	Implementation of plan resulted in an average 17% less N applied.	(Eory et al., 2015)
Improved Grasses	Minimized concentrate inputs Forage based on grasses with high proportion of dry matter digestibility	(Speedy and Sansoucy, 1998)

	For extensive systems, herd sizes were kept the same, but stocking density per ha was increased. Improved grasses measure was implemented on the stocked area. Fertiliser was only applied to land utilised under the measure.	
Increase Concentrate	Increase amount of concentrate as single supplement by 25%	(Hristov et al., 2013b)
Manure Broadcast	Utilised Manner NPK, achieving 6% N content for slurry.	(Nicholson et al., 2013)

Table A.2. Marginal Abatement Cost Curve Cost Parameters

Name	Details	Reference
Anaerobic Digestion	Establishment and maintenance cost of anaerobic digester	(Casasola et al., 2018b)
Ventilation & Sprinklers	Instalment cost and water consumption of sprinkler	(Gunn et al., 2019)
Ventilation & Sprinklers	Water rate	(ARESEP, 2017)
Precision Feeding	Tools for precision feeding	(Piccioli-Cappelli et al., 2019)
Precision Feeding	Price of software, scale indicator, and NIRS for precision feeding	Vendor information
Silvopastoral systems	Establishment and maintenance cost of silvopastoral system	(Jimenez-Trujillo et al., 2011)
Genetic Improvement	Price of Holstein cattle	Vendor information
Manure Application	Application rate of manure using different technologies	(Chen et al., 2013)
Manure Application	Contractor rate to apply manure	(Craig, 2017)
General Rates	Minimum wage of labour	(MTTS, 2019)
General Rates	Inflation rate	(IMF, 2019)

Table A.3. Participating Local Organisations

Name	Details	Link
CATIE	The Tropical Agricultural Research and Higher Education Centre	https://catie.ac.cr/
INTA	National Institute of Innovation and Transfer in Agricultural Technology	https://www.inta.go.cr/
MAG	Ministry of Agriculture Costa Rica	http://www.mag.go.cr/
UNA	National University of Costa Rica	https://www.una.ac.cr/
UCR	University of Costa Rica	https://www.ucr.ac.cr/
TEC	The Costa Rica Institute of Technology	https://www.tec.ac.cr/
UTN	National Technical University	https://www.utn.ac.cr/
Dos Pinos	Dos Pinos Milk Producers Cooperative	https://www.cooperativadospinos.com/
PROLECHE	National Chamber of Milk Producers (Costa Rica)	http://www.proleche.com/
CORFOGA	Livestock Corporation	https://www.corfoga.org/
SA	Sigma Alimentos	https://www.sigma-alimentos.com/en/

Table A.4. Variable definitions and sample descriptive statistics by farm typology

	Farm typology				
Variables	DPEL	SD_E_L	SD_I_L	SD_I_U	SD_SI_U
Farm characteristics					
Farm Size (ha)	251.0	80.7	59.1	49.7	57.4
Farm inputs & consumption					
Urea Fertilizer (kg yr-1)	604.4	842.4	980.0	1406.4	944.1
N (NPK) (kg yr-1)	2750.4	1195.7	916.2	1477.7	1874.4
P205 (NPK) (kg yr-1)	4569.3	1879.0	3043.8	3137.5	3633.6
K20 (NPK) (kg yr-1)	12256.9	2922.4	7745.0	9004.2	10516.4
Other N Fertilisers (kg yr-1)	837.7	2519.4	1755.0	875.5	1594.8
Fuel Consumption (l yr-1)	3657.6	1856.8	2238.2	3342.0	3031.6
Electricity (Kw-h yr-1)	21260.3	7222.8	12040.2	16603.1	16112.7
Livestock outputs and herd characteristics					
Average Milk Production (L day -1)	9.3	16.0	16.7	20.7	18.2
# Milking cows	130.0	81.0	77.0	78.0	75.0
# Dry cows	49.0	27.0	21.0	17.0	18.0
# Heifers < 2 yrs	116.0	41.0	44.0	44.0	46.0
# Heifers > 2 yrs	0.0	0.0	0.0	0.0	0.0
# Male calves	0.0	1.0	0.0	0.0	0.0
# Female calves	63.0	33.0	19.0	17.0	22.0
# Steers	0.0	1.0	0.0	1.0	0.0
# Bulls	0.0	1.0	0.0	0.0	0.0
Total Liveweight Bought (kg)	2,734	2,492	4,656	1,864	3,600

Total Liveweight Sold (kg)	6,370	1,2784	7,671	1,0159	8,411

**DP_E_L= Dual-purpose Extensive in the Lowlands; SD_E_L=Specialised Dairy Extensive in the Lowland; SD_I_L=Specialised Dairy Intensive Lowland; SD_I_U= Specialised Dairy Intensive in the Uplands; SD_SI_U= Specialised Dairy Semi-Intensive in the Uplands

Table A.5. Summary of assumptions considered by expert panel

	Parameters	Unit	Base line	TM AD	TM V&S	TM PF	TM SP	EF AH	EF GI	BF IC	PM LM	PM IGV	PM NMP	MMBC
DP_E_L	**urea_fertiliser_use**	kg per ha	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	0.61	2.41
	other_n_fertiliser_use	kg per ha	14.3	11.01	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	6.1	14.09
	grass_utilisation	t per ha per year	3.72	3.72	3.8	3.82	4.64	3.29	3.72	3.67	2.7	3.27	3.72	3.72
	stocking_rate	# per ha	1.14	1.14	1.14	1.14	1.42	1.1	1.14	1.14	1.14	3.3	1.14	1.14
	total_n_animals	#	285.4	285.4	285.4	285.4	285.4	277.3	285.4	285.4	285.4	285.4	285.4	285.4
	Milk yield	litres per day	9.26	9.26	10.25	10.46	9.26	9.93	10.18	11.91	9.26	9.26	9.26	9.26
SD_E_L	**urea_fertiliser_use**	kg per ha	10.43	10.43	10.43	10.43	10.43	10.43	10.43	10.43	9.24	10.43	6.30	10.43
	other_n_fertiliser_use	kg per ha	46.01	41.57	46.01	46.01	46.01	46.01	46.01	46.01	40.76	46.01	19.32	45.67
	grass_utilisation	t per ha	5.32	5.32	5.48	5.51	6.65	4.65	5.32	5.10	4.19	5.68	5.32	5.32
	stocking_rate	# per ha	1.89	1.89	1.89	1.89	2.36	1.85	1.89	1.89	1.89	3.75	1.89	1.89
	total_n_animals	#	152.3	152.3	152.3	152.3	152.3	149.4	152.3	152.3	152.3	152.3	152.3	152.3
	Milk yield	litres per day	16.01	16.01	17.0	17.21	16.01	17.17	17.61	19.58	16.01	16.01	16.01	16.01
SD_I_L	**urea_fertiliser_use**	kg per ha	16.57	16.57	16.57	16.57	16.57	16.57	16.57	16.57	13.42	16.57	16.57	16.57
	other_n_fertiliser_use	kg per ha	45.18	40.53	45.18	45.18	45.18	45.18	45.18	45.18	36.58	45.18	44.70	44.77
	grass_utilisation	t per ha	5.81	5.81	6.01	6.05	7.26	5.02	5.81	5.45	4.50	6.37	5.81	5.81
	stocking_rate	# per ha	2.31	2.31	2.31	2.31	2.88	2.25	2.31	2.31	2.31	2.31	2.31	2.31

	total_n_animals	#	136.40	136.4	136.4	136.4	136.4	133.32	136.4	136.4	136.4	136.4	136.4	136.4
	Milk yield	litres per day	16.75	16.75	17.74	17.95	16.75	17.96	18.42	21.46	16.75	16.75	16.75	16.75
SD_I_U	**urea_fertiliser_use**	kg per ha	28.28	28.28	28.28	28.28	0.00	28.28	28.28	28.28	18.7	28.28	28.28	28.28
	other_n_fertiliser_use	kg per ha	47.32	38.41	47.32	47.32	0.00	47.32	47.32	47.32	31.30	47.32	46.95	47.01
	grass_utilisation	t per ha	6.25	6.25	6.49	6.54	7.81	5.33	6.25	5.47	4.82	7.54	6.25	6.25
	stocking_rate	# per ha	2.69	2.69	2.69	2.69	3.36	2.62	2.69	2.69	2.69	2.69	2.69	2.69
	total_n_animals	#	133.6	133.6	133.6	133.6	133.6	130.52	133.6	133.6	133.6	133.6	133.6	133.6
	Milk yield	litres per day	20.72	20.72	21.71	21.92	20.72	22.22	22.79	26.73	20.72	20.72	20.72	20.72
SD_SI_U	**urea_fertiliser_use**	kg per ha	16.46	16.46	16.46	16.46	16.46	16.46	16.46	16.46	10.70	16.46	16.46	16.46
	other_n_fertiliser_use	kg per ha	60.48	50.68	60.48	60.48	60.48	60.48	60.48	60.48	39.30	60.48	60.17	60.21
	grass_utilisation	t per ha	5.5	5.5	5.7	5.74	6.87	4.71	5.5	5.12	4.25	6.4	5.5	5.5
	stocking_rate	# per ha	2.34	2.34	2.34	2.34	2.92	2.28	2.34	2.34	2.34	2.34	2.34	2.34
	total_n_animals	#	134.0	134.0	134.0	134.0	134.0	130.78	134.0	134.0	134.0	134.0	134.0	134.0
	Milk yield	litres per day	18.18	18.18	19.17	19.38	18.18	19.49	19.99	23.48	18.18	18.18	18.18	18.18

*Typology Key: SD_E_L = Specialised Dairy Extensive Lowland; SD_I_L = Specialised Dairy Intensive Lowland; SD_SI_U = Specialised Dairy Semi-Intensive Uplands; SD_I_U = Specialised Dairy Intensive Uplands; DP_E_L = Dual-purpose Extensive Lowlands.

*Measures Key: *TM = Technical Measure; EF = Efficiency Measure; PM= Pasture Measure; MM= Manure Measure

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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