Agricultural Systems 166 (2018) 1–9

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Opportunities to improve sustainability on commercial pasture-based dairy farms by assessing environmental impact

Craig Galloway[a,*], Beatrice Conradie[e], Heidi Prozesky[c,d], Karen Esler[a,b]

[a] Department of Conservation Ecology and Entomology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
[b] Centre for Invasion Biology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
[c] Centre for Research on Evaluation, Science and Technology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
[d] DST-NRF Centre of Excellence in Scientometrics and STI Policy, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa.
[e] School of Economics and Centre for Social Science Research, University of Cape Town, Private Bag X1, Rhodes Gift 7703, South Africa.

ARTICLE INFO

Keywords:
Pasture-based dairy
Environmental impact
Nutrient budget
Carbon footprint

ABSTRACT

For pasture-based dairy farming to become more sustainable, the negative environmental impacts associated with milk production must be minimized. These negative impacts include eutrophication, ammonia emissions and greenhouse gas (GHG) emissions. Two tools, a nutrient budget and a carbon footprint calculator, allow farm-level assessments of these negative impacts. In this study, a nutrient budget was used to calculate the efficiency of nitrogen and phosphorous use, and a carbon footprint calculator was used to calculate GHG emissions. Farm system descriptors were used to identify the farm systems that had the lowest environmental impact. Soil carbon was measured as an indicator of soil health, and the link between soil health, nutrient use efficiency and GHG emissions was examined. Nitrogen and phosphorous were not efficiently utilized on the farms included in this study, with a large excess of nutrients imported onto the farms each year. The average use efficiency was 29% for nitrogen, and 36% for phosphorous. The GHG emissions per liter of milk production were higher on the farms included in this study than found in previous studies on dairy farms, with an average of 1.39 kg of carbon dioxide equivalents emitted per kilogram of energy-corrected milk. Farm systems which optimized milk production on the available land, while applying the least amount of fertilizer and feeding the least amount of purchased feeds per milk produced, had the lowest environmental impact. Farms with higher soil carbon levels had higher nitrogen use efficiencies and lower GHG emissions. This is the first South African research to examine environmental impact on pasture-based dairy farms in this manner. It is possible for pasture-based dairy farmers to reduce the environmental impact of milk production by adopting some of the principles identified in this study.

1. Introduction

It has become apparent over the past 30 years that the agricultural sector faces a challenge to increase production without an associated increase in negative environmental impacts (Tilman et al., 2002). Farming has many potentially negative environmental impacts, including loss of biodiversity, eutrophication, ammonia emissions, greenhouse gas (GHG) emissions and inefficient resource use (Food and Agriculture Organization of the United Nations (FAO), 2010). By understanding and assessing the negative environmental impacts of dairy farming practices, ways to mitigate these impacts can be identified, while maintaining/increasing production (Thomassen and De Boer, 2005; Capper et al., 2009; Food and Agriculture Organization of the United Nations (FAO), 2010). Viewed from the perspective of the triple bottom line of economic, social and ecological sustainability (Rigby et al., 2001; Van Calker et al., 2005), reducing these impacts through appropriate farm management is directly related to the ecological aspect, but also significantly impacts the economic aspect (Galloway et al., 2018), while being a farmer's social responsibility.

There are two, broad types of dairy farm. The one type is a total mixed rations (TMR), full feed or confinement dairy farm where dairy cows are kept in a confined space and their entire required feed is provided as a mixed ration (O'Brien et al., 2014). The other is a pasture-based dairy farm where the majority of a cow's nutritional requirement is met through grazing pastures, which are grown on the farm and supplemented by purchased grain-based concentrates and dried or conserved forage (roughage). The two farm types employ very different practices and mechanisms to reduce environmental impact and improve efficiency, but comparisons between them are few (Scholtz et al., 2013; O'Brien et al., 2014). The two types are also not always operated

* Corresponding author.
E-mail address: craig@traceandsave.com (C. Galloway).

https://doi.org/10.1016/j.agsy.2018.07.008
Received 13 September 2017; Received in revised form 29 March 2018; Accepted 9 July 2018
Available online 19 July 2018

exclusively of each other. For example, some farmers implement TMR through winter, while implementing pasture-based through the rest of the year. The focus of this study is on pasture-based dairy farms.

Two tools, a nutrient budget and a carbon footprint calculator, are useful in assessing aspects of agriculture's environmental impacts (Cichota & Snow, 2009; Food and Agriculture Organization of the United Nations (FAO), 2010; Rotz et al., 2010; Gourley et al., 2012). Numerous other agri-environmental indicators exist (Halberg et al., 2005; Langeveld et al., 2007), but these two indicators are relevant to this study as they meet four important criteria: 1) they are established, widely applied measures of environmental impact, 2) they are sensitive to changes in farm management, 3) they assess the whole-farm system, and 4) they are easily understood by farmers. Although many studies have used nutrient budgets or carbon footprints, currently only Thomassen and De Boer, 2005and Pérez Urdiales et al. (2016) have incorporated both into an assessment of the environmental impact of dairy farming (in the Netherlands and Spain respectively). The limitation of using a nutrient budget and a carbon footprint calculator is that they do not assess the full extent of environmental impacts associated with dairy farming (Thomassen and De Boer, 2005).

Nutrient management is an important aspect of sustainable dairy farming. Inefficient nutrient use results in an excess of nitrogen (N) and phosphorous (P) being imported onto a farm, which could harm the environment and reduce profits (Spears et al., 2003; Monaghan et al., 2007; Gourley et al., 2012; Galloway et al. 2018). Excess N causes nitrate contamination in groundwater, and excess P leads to high soil P levels and eutrophication of surface water (Dou et al., 2001; Gourley et al., 2012). Nitrogen from fertilizer and manure is lost to the atmosphere in the form of nitrous oxide gas, contributing to climate change (Spears et al., 2003). Improving nutrient use efficiency (NUE) is therefore imperative in limiting the environmental impact of agriculture (Zhang et al., 2015).

To inform improved nutrient management on farms, measures of NUE and nutrient loss are needed (Spears et al., 2003; Clark et al., 2007). Direct measurement of nutrient loss is, however, challenging and expensive (Cichota & Snow, 2009), as it requires measuring the quantity of the different nutrients in their different forms (e.g. nitrates, ammonium, nitrous oxide, phosphates) from varying sources. An alternative is to quantify nutrient surpluses using a nutrient-budget approach (Oenema et al., 1998; Dou et al., 2001; Ondersteijn et al., 2002; Spears et al., 2003; Cichota & Snow, 2009; Gourley et al., 2012). Nutrient budgets have not been studied in South Africa, and therefore the nutrient use efficiencies of South African dairy farms are unknown.

Another significant environmental impact associated with dairy farming is GHG emissions (Food and Agriculture Organization of the United Nations (FAO), 2010; de De Léis et al., 2015). Greenhouse gas emissions are associated with global climate change, which is one of the most significant environmental challenges of this century (Rotz et al., 2010) and a key challenge facing the South African agricultural sector (Middelberg, 2013). The extent and sources of farm GHG emissions resulting from agricultural practices can be measured using a carbon footprint calculator (Food and Agriculture Organization of the United Nations (FAO), 2010; Rotz et al., 2010). This method has been used extensively in the assessment of the environmental impact of dairy farms (e.g. Food and Agriculture Organization of the United Nations (FAO), 2010; Rotz et al., 2010; Flysjö et al., 2011; De Léis et al., 2015). Currently, there is no evidence of any research on carbon footprints at an individual farm level on dairy farms in South Africa.

When addressing environmental impacts on farms, soil management is important to consider (Paustian et al., 2016). Healthy soil is a critical management goal of sustainable agriculture (Parr et al., 1992; Doran et al., 1996; Doran, 2002; Eisenhauer et al., 2017; Food and Agriculture Organization of the United Nations (FAO), 2017). A prime indicator of soil health is soil carbon (C). Higher levels of soil C improve the biological, chemical and physical properties and functions of the soil (Fageria, 2012; Food and Agriculture Organization of the United Nations (FAO), 2017).

The trade-off that exists between agricultural production and environmental impact is important to consider when addressing agricultural sustainability, as economic and environmental goals often conflict (Tilman et al., 2002). Farm system descriptors such as stocking rate, milk production per cow and nitrogen fertilizer applied per hectare are widely used by dairy farmers and are indicative of the farm system that each farm employs (P Terblanche 2016, personal communication, 1 June). The farm system in this study's context relates to the stocking rate, feeding practices, fertilizer practices, and how these interrelate. Showing the relationship between NUE, GHG emissions and farm system descriptors can assist in rendering environmental impact measures more relatable to farmers and their farm management practices (Halberg et al., 2005).

Here, measures that assess environmental impact, such as nutrient budgets and carbon footprints, were therefore used to study the environmental impact of commercial pasture-based dairy farms in South Africa's Eastern Cape. The measurement of soil C, an indicator of soil health, was included to examine the links between NUE, GHG emissions and soil health. It was further asked which farm system had the least environmental impact. This research therefore provides valuable insights to farmers, researchers and consultants aiming to decrease the environmental impact of pasture-based dairy farms. The inclusion of both a nutrient budget and a carbon footprint, along with farm system descriptors, and soil carbon measures overcomes the benchmarking challenges associated with only assessing nutrient budgets without accounting for different characteristics between farms (Mu et al. 2017).

2. Methods

2.1. Data collection

The dairy farms included in this study are in the western part of the Eastern Cape, South Africa. The Eastern Cape is the largest milk-producing province in South Africa, contributing more than a quarter of the country's total milk production. The data for this study, secondary data obtained from Trace & Save, were collected on farms that both sell milk to Woodlands Dairy and participate in the Woodlands Dairy Sustainability Project (WDSP). Trace & Save is an independent consulting company that implements the WDSP. Trace & Save aims to encourage and facilitate the implementation of sustainable agricultural practices, and to measure, using proxies for various dimensions of sustainability, the participating farms' changes over time. Farmers can participate voluntarily in the WDSP, as it is provided as an optional service to all farmers who sell milk to Woodlands Dairy. This obviously results in a non-random sample of farms included in this study, especially selecting for farmers which have shown an interest in sustainability.

Secondary data, such as the Trace & Save dataset, are those obtained from a dataset not designed and intended for this specific study. This has the advantage of saving cost and time, is most often high-quality data and provides more comprehensive data from a longer period than what might be possible for an individual researcher to collect (Bryman, 2012). At the time of this study, the Trace & Save dataset was comprised of yearly production data for farms collected over a period between one-and-five-years, depending on how long the farm had been participating in the WDSP. Data relevant to this study are listed in Table 1. To manage the variability in data availability across time, while simultaneously using as much of the collected data as possible, each farm's annual data were treated as a single observation. Although this could potentially result in biases due to certain farm systems being over-represented in the population, there was enough interannual variation on the farms with more than one year of data included, and the climatic conditions differed enough among years, to make this dataset appropriate for the aims of the study. As discussed, there are many advantages to using secondary data, but a disadvantage is that certain

Table 1
Variables on which data were extracted from the Trace & Save dataset, the units in which they are collected (where applicable), and the tools or measures for which they are used.

Variable	Unit	Tools/measures
Farm inputs		
Fertilizer applied		NB; CF; FS
- Type		
- Quantity	t	
Fertilizer application method		CF
Purchased concentrates fed		NB; FS
- Type		
- Quantity	t	
Purchased roughage fed		NB; FS
- Type		
- Quantity	t	
Fuel (diesel and petrol) usage	L	CF
Electricity usage	kWh	CF
Cattle bought		NB
- Number		
- Live weight	kg	
On-farm variables		
Total farm (irrigated and dryland) area	ha	NB; CF; FS
Annual rainfall	mm	Climate
Annual average daily temperature for the region	°C	CF
Soil carbon	%	CF; Soil health
Soil bulk density	g/cm^3	CF
Soil texture		CF
pH	pH	CF
Crop and/or pasture types		CF
Crop residue management	t/ha	CF
Cows in milk, dry cows and heifers		CF
- Number		
- Live weight	kg	
- Daily weight gain	kg	
Manure management system (IPCC 2006)	%	CF
Farm outputs		
Milk production	L	NB; CF; FS
Milk butterfat content	%	CF; FS
Milk protein content	%	CF; FS
Crops sold – type and quantity		NB
- Type		
- Quantity	t	
Cattle sold and culled		NB
- Number		
- Live weight	kg	

NB – nutrient budget; CF – carbon footprint; FS – farm system descriptors.

data were not available. For example, measures for reproduction (e.g. calving interval, days dry and calves born) would have contributed to this study, but these data were not collected by Trace & Save.

One of two broad systems are adopted on dairy farms in the raising of heifer cattle to replace older milking cows that have been culled from the herd. Heifers are either kept on the same farm as the milking cows; or they are moved to a different farm, raised, and then returned to the milking farm when they are about to calve. Farms following different systems are not directly comparable, since they differ in terms of the number of cattle kept on the farm, pasture area and/or feed inputs required. For the purposes of this study, only data from farms that raise heifers on the milking farm were selected from the dataset, as more farms follow this system, and the data on these farms provide a more comprehensive assessment of the environmental impact of pasture-based dairy farms. This selection, and the fact that some farms had provided more than one year's data, resulted in a dataset comprising 93 “cases” of yearly data, originating from 45 farms.

In addition to the annual production data collected from farmers, composite soil samples are taken on a regular (every year and a half) basis on each of the farms participating in the WDSP. On average, one composite sample is taken for each 12.5 ha of the milking platform. Each composite sample is made up of 8–15 individual cores taken with a soil auger, with the soil being bulked from which a subset is taken for analysis. The soil samples are obtained by trained, full-time staff of the WDSP whose primary responsibility is to take soil and water samples, with assistance from the fieldworkers. The main purpose of these samples is to provide farmers with feedback and insight on their farm's current soil health status. The soil samples are taken according to South African standards (Non-Affiliated Soil Analysis Work Committee, 1990). Total C (analyzed by a LECO® elemental combustion analyzer) is analyzed by Bemlab, a South African National Accreditation System accredited laboratory. The average total C (%) at a 15 cm depth was therefore obtained from the Trace & Save dataset.

2.2. Data processing

2.2.1. Nutrient budget

Nutrient budgets involve using nutrient balance-sheets to take a farm-gate (also called whole-farm) approach where all nutrients that enter or leave the farm “via the farm gate” are recorded (Oenema et al., 2003; Gourley et al., 2012). Because it does not rely on specialized soil variables that are costly to measure and difficult to measure accurately, the approach is useful as a whole-farm environmental impact indicator.

Trace & Save uses a nutrient budget tool based on the nutrient accounting system implemented in the Netherlands in 1998 (Ondersteijn et al., 2002). This nutrient budget is compiled annually by the Trace & Save fieldworkers, using the data collected from the farms participating in the WDSP. The variables used in the calculation are indicated in Table 1. The nutrient budget is a simple calculation of the total nutrients imported onto the farm, and removed from the farm, over an annual period. These totals are divided by the total farm area, resulting in the kilograms of nutrients imported per hectare and the kilograms of nutrients removed per hectare. The NUE for each farm is calculated based on the nutrients removed per hectare as a percentage of the

Table 2
The sources of imported and removed nutrients, including the nitrogen and phosphorous content, used for each source of nutrients.

Nutrient source	Nitrogen content	Phosphorous content
Imported		
Fertilizer	Specific to type of fertilizer – provided by farmer or fertilizer salesperson as N% of product	Specific to type of fertilizer – provided by farmer and/or fertilizer salesperson as P% of product
Feed	Specific to type of feed – provided by farmer, feed company or https://www.feedipedia.org/ database in g N/kg feed	Specific type of feed – provided by farmer, feed company or https://www.feedipedia.org/ database in g P/kg feed
Cattle	Standard N levels – cows 25.3; bull calves 29.4 and heifers 27.4 g N/kg live weight	Standard P levels – cows 7.4; bull calves 8.0 and heifers 7.7 g P/kg live weight
Removed		
Milk	Calculated based on milk protein %. Nitrogen level (g N/kg) = milk protein % × 0.16 (N content of protein) × 1.028 (weight of milk) × 1000	Standard P levels – 0.9 g P/kg milk produced
Cattle	Standard N levels – cows 25.3; bull calves 29.4 and heifers 27.4 g N/kg live weight	Standard P levels – cows 7.4; bull calves 8.0 and heifers 7.7 g P/kg live weight
Feed	Specific to product – provided by farmer, feed company or https://www.feedipedia.org/ database in g N/kg feed	Specific to product – provided by farmer, feed company or https://www.feedipedia.org/ database in g P/kg feed

nutrients imported per hectare.

The N and P levels for each of the imported and removed nutrient sources are detailed in Table 2. These values for each source were multiplied by the weight of the source imported or removed, providing a total amount of N and P imported or removed in that specific product or produce. Three limitations with this calculation are that the nutrients imported in irrigation water are not accounted for, N inputs from biological fixation from legumes have not been included, and the P levels for milk, and the N and P levels for cattle, were not recorded per farm making the use of standard levels necessary. None of these forms part of the Trace & Save dataset.

2.2.2. Carbon footprint

Each year, Trace & Save calculates the carbon footprint of each farm participating in the WDSP project. A carbon footprint can be calculated based on one, or a combination, of the following types of emissions: Scope 1 (direct GHG emissions from company owned or controlled sources), Scope 2 (indirect GHG emissions from purchased energy) and/or Scope 3 (other indirect emissions, for example resulting from the production of purchased materials). Although Trace & Save calculates the full scope 1, scope 2 and scope 3 carbon footprint for each farm, only certain accurately recorded scope 1 and 2 emissions were included in this study, i.e. on-farm fuel use, enteric fermentation, manure management, crop production (all scope 1) and electricity (scope 2). While other sources of GHG emissions exist on dairy farms, these are the major sources of scope 1 and 2 emissions. The calculations of the Trace & Save carbon footprint for the other scope 1 emissions (i.e. waste incineration and fugitive emissions) are based on inaccurate estimated data collected from farmers and would also be insignificant to the scope 1 GHG emissions resulting from farm management practices. Numerous forms of GHG emissions result from farm management practices, for example carbon dioxide, methane and nitrous oxide. These greenhouse gases each have different Global Warming Potentials (GWP). For example, methane has 25 times the GWP of carbon dioxide, and nitrous oxide has 298 times the GWP of carbon dioxide (De Léis et al., 2015). A carbon footprint therefore calculates total GHG emissions relative to the effect of carbon dioxide equivalents (CO_2e).

The Trace & Save carbon footprint calculation is based on established GHG emissions protocols and norms. Emissions from fuel use were calculated based on the United Kingdom Department of Environment, Food and Rural Affairs (DEFRA) (2012) emissions factors, 2.6769 kg CO_2e/l for diesel and 2.3144 kg CO_2e/l for petrol (DEFRA, 2012). The emissions from enteric fermentation were calculated using a tier 2 approach based on formulas found in the International Panel on Climate Change (IPCC), 2006a guidelines, pages 10.10 to 10.23. Emissions from manure management were calculated using a combination of IPCC tier 1 and 2 methodologies (International Panel on Climate Change (IPCC), 2006a), and the formulas can be found in the International Panel on Climate Change (IPCC), 2006a guidelines, pages 10.35 to 10.59 and 10.77 to 10.78. Manure emissions include both the manure captured in the dairy parlor and yard, and what is deposited on the pasture areas. Emissions from electricity use were based on the emission factor provided by the South African national power regulator, Eskom (0.99 kg CO_2e/kWh). The emissions from crop production were calculated using The Cool Farm Tool Version 2.0 - beta 1 (Van Tonder and Hillier, 2014; https://www.coolfarmtool.org/), which is based on the International Panel on Climate Change (IPCC), 2006b methodology. Fertilizer application rates, crop residue management practices, climate and soil indicators (Table 1) influencing GHG emissions from crop production are entered into the Cool Farm Tool, which provides an output of the total GHG emissions from crop production. The total GHG emissions (in kilograms of CO_2e) for each source associated with farm management practices were obtained from the Trace & Save dataset.

The two main products from pasture-based dairy farms in the Eastern Cape are milk and animal sales - bull calves, cull cows and heifers. The GHG emissions from each farm were allocated between milk and meat. The average prices of bull calves (R 3/kg), cull cows (R 15/kg) and heifers (R 30/kg) between 2013 and 2017 were used to calculate the income from the sale of these animals. The average price of milk (R 4.15/l) was used to calculate the income from milk production. Like Rotz et al. (2010), the percentage emissions allocated to milk production for each farm was calculated as: income from milk/(income from milk + income from meat). Milk production contributed 93.5% of the income on the farms included in this study. Only the GHG emissions allocated to milk production are discussed in the rest of the paper, as these are by far the most significant contributor to emissions. A functional unit of 1 kg of energy-corrected milk (ECM), as in Sjaunja et al. (1990), was used to provide fat-and-protein-corrected milk yield (e.g. Rotz et al., 2010; Flysjö et al., 2011). ECM is defined as raw milk with 4.10% fat and 3.30% protein.

2.2.3. Farm system descriptors

The data collected on each farm by Trace & Save (Table 1) allows for the calculation of farm system descriptors. Descriptors such as stocking rate, milk production per cow, milk production per hectare, concentrates fed per unit of milk production, roughage fed per unit of milk production, N fertilizer applied per hectare per year and P fertilizer applied per hectare per year were calculated for the 93 “cases” included in this study.

2.3. Data analysis

The measures of environmental impact, farm system descriptors and soil carbon were tested for strength of association. A Shapiro-Wilk test for normality was conducted using IBM SPSS Statistics 24. All of the data, except milk production per cow, purchased concentrates fed per milk produced and GHG emissions resulting from crop production, were nonparametric. Spearman correlations were therefore calculated to test for association between the variables, using IBM SPSS Statistics 24. All reported measures of variation are standard deviations.

The composite NUE of each farm was calculated by dividing the sum of N and P removed by the sum of N and P imported. Farms were ranked from highest to lowest NUE and then grouped into NUE terciles. Similarly, farms were ranked from lowest to highest GHG emissions, and grouped into GHG emission terciles. The terciles were used to compare the mean farm system descriptors of farms grouped according to the highest, moderate and lowest NUE and GHG emission. A Shapiro-Wilk test was used to test for the approximate normal distribution of the dependent variable (farm system descriptors) for each of the independent variable (NUE and GHG emissions terciles) categories. The test showed that some of the dependent variables were not normally distributed. A Kruskal-Wallis test was therefore used to test for variation in mean farm system descriptors between groups using IBM SPSS Statistics 24.

3. Results

3.1. Environmental impact of pasture-based dairy farming

The average on-farm N-use efficiency (percentage of N imported that is removed) was 29% (± 12%), with an average of 383 kg N/ha imported and 99 kg N/ha removed. An excess of N, to the extent of an average of 284 kg/ha per year, was generated by these dairy farms. N use efficiency ranged from a minimum of 9% to a maximum of 76% (note: this farmer applied 0 kg/ha N fertilizer). The average P use efficiency (percentage of P imported that is removed) of 36% (± 23%) resulted from an average of 58 kg P/ha imported and 16 kg P/ha removed. The range of P-use efficiency was 10% to 195% (i.e. almost twice as much P was removed as was imported). The single practice with the highest impact relating to NUE was fertilizer application, with fertilizer being the largest source of imported N and P. An average of 260 (± 157) kg N/ha and 28 (± 40) kg P/ha was applied in fertilizer.

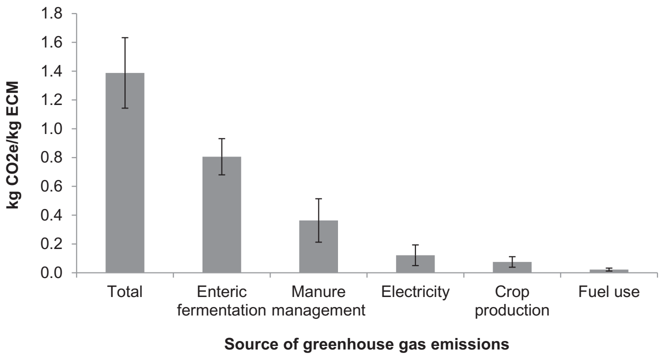

Fig. 1. Average greenhouse gas emissions of pasture-based dairy farms, and average contribution of the different sources of greenhouse gas emissions to farm carbon footprints (n = 93). The error bars represent standard deviations.

An average of 1.39 (± 0.24) kilograms of carbon dioxide equivalents were emitted per kilogram of energy-corrected milk (kg CO_2e/kg ECM). However, GHG emissions ranged widely from a low of 0.94 kg CO_2e/kg ECM to a high of 2.07 kg CO_2e/kg ECM. The largest contributor to environmental impact, in terms of GHG emissions, was methane from enteric fermentation (Fig. 1).

There was a negative correlation between NUE and GHG emission intensity. Phosphorous use efficiency and GHG emissions were, however, not correlated (Table 3). The main contributor to GHG emissions associated with crop production is N fertilizer application, therefore it is not surprising that it was negatively correlated with N use efficiency ($r = -0.54$, $p < .001$).

3.2. The association between environmental impact, soil carbon and farm system

Soil C was positively correlated with N-use efficiency and negatively correlated with GHG emissions (Table 3). The farm system descriptors most strongly associated with N- and P-use efficiency are N- and P-fertilizer-application rates, as indicated by the negative correlations between these factors. N-use efficiency was positively correlated with milk production per cow and milk production per hectare, and negatively correlated with concentrates fed relative to milk production. The farm system descriptor of purchased concentrates fed per milk production was calculated as the total megajoules of concentrates fed per kilogram of ECM produced, which provides a measure of feed conversion efficiency. A similar descriptor was calculated from the megajoules fed from purchased roughage. GHG emission intensity was negatively correlated with stocking rate, milk production per hectare and milk production per cow. There were positive correlations between purchased concentrates fed per milk produced and GHG emission intensity (Table 3).

An average composite NUE (N plus P removed as a percentage of N plus P that is imported) of 41%, 26% and 19% was found among the farms in the highest, middle and lowest NUE terciles respectively. The farm system descriptors which were significantly different among the terciles were milk production per cow, milk production per hectare, N fertilizer application rate, purchased concentrates fed per milk produced and purchased roughage fed per milk produced. N and P fertilizer application rate and purchased concentrates fed per milk produced increased from the highest to lowest tercile, whereas milk production per cow, milk production per hectare and purchased roughage fed per milk produced were highest for the middle tercile (Table 4). The average GHG emissions were 1.17 kg CO2e/kg ECM, 1.33 kg CO2e/kg ECM and 1.66 kg CO2e/kg ECM for the lowest, middle and highest terciles respectively. Stocking rate, milk production per hectare, purchased concentrates fed per milk produced, purchased roughage fed per milk produced and irrigated area percentage were all significantly different among terciles. Stocking rate, milk production per hectare and irrigated area percentage were all highest in the middle tercile. Purchased concentrates fed per milk produced were similar in the first two terciles, increasing in the third (Table 5).

In terms of farm system descriptors, soil C was positively correlated with milk production per cow, and negatively correlated with stocking rate, purchased roughage fed per milk produced and N fertilizer rate. Stocking rate, milk production per hectare, percentage of area irrigated, N fertilizer application rate and P fertilizer application rate were all positively correlated, indicating that these factors have associations. Percentage of area irrigated was negatively correlated with purchased concentrates fed per milk produced (Table 3).

4. Discussion

4.1. The environmental impact of pasture-based dairy farming

The extent of the environmental impacts indicated by the use of a nutrient budget and a carbon footprint calculator differed greatly among the farms included in this study. There was a negative correlation between the results from the N nutrient budgets and the carbon footprints, indicating some association between the environmental impacts assessed by these measures. This negative association was expected, as shared, direct sources of environmental impact are assessed

Table 3
Spearman's correlation coefficients showing relationships between environmental impact measures, farm system descriptors and soil health measures on pasture-based dairy farms (n = 80).

Environmental impact, farm system and soil health measures	N UE	P UE	GHG	Stock. rate	Milk per cow	Milk per ha	Conc.	Rough.	N fert.	P fert.	Soil C	Irr.
	Spearman's rho											
N use efficiency (%)	1	0.47**	−0.35**	0.17	0.21*	0.21*	−0.28**	0.00	−0.46**	−0.15	0.25*	0.11
P use efficiency (%)		1	0.01	−0.08	0.00	−0.07	−0.12	−0.04	−0.43**	−0.70**	0.07	−0.01
GHG emission intensity (kg CO2e/kg ECM)			1	**−0.22***	**−0.26***	**−0.26***	**0.30****	0.01	0.02	−0.18	**−0.29****	−0.13
Stocking rate (Cows in Milk/ha)				1	0.01	**0.97****	−0.17	**0.32****	**0.60****	**0.37****	**−0.22***	**0.71****
Milk production (kg ECM/cow)					1	**0.23***	**−0.40****	−0.03	0.19	**0.36****	**0.28****	**0.23***
Milk production (kg ECM/ha)						1	**−0.25***	**0.34****	**0.62****	**0.42****	−0.15	**0.74****
Purchased concentrates (MJ/kg ECM)							1	−0.14	−0.16	**−0.32****	−0.11	**−0.34****
Purchased roughage (MJ/kg ECM)								1	0.16	0.03	**−0.21***	**0.24***
N fertilizer (kg N/ha)									1	**0.65****	**−0.23***	**0.44****
P fertilizer (kg P/ha)										1	0.01	**0.32****
Soil total C (%)											1	−0.13
Irrigated area (%) [ha irrigated/total ha]												1

Bold values indicate a significant correlation.
* p ≤ .05.
** p ≤ .01.

Table 4
Farm system descriptors grouped according to composite nutrient-use-efficiency terciles.

Farm system descriptors	NUE tercile			Kruskal-Wallis H
	Highest (n = 27)	Middle (n = 26)	Lowest (n = 27)	
	Mean ± std deviation			
Composite NUE (%)	41% ± 9%	26% ± 3%	19% ± 3%	
Stocking rate (CiM/ha)	2.43 ± 1.29	2.85 ± 1.44	2.03 ± 0.85	5.48
Milk production (kg ECM/cow)	6821 ± 925	6914 ± 816	6358 ± 898	**6.81***
Milk production (kg ECM/ha)	16,629 ± 8811	19,053 ± 7968	12,936 ± 5669	**9.02***
Purchased concentrates fed (MJ/kg ECM)	4.35 ± 0.97	4.70 ± 1.09	5.21 ± 0.95	**10.03****
Purchased roughage fed (MJ/kg ECM)	1.42 ± 1.49	2.32 ± 1.37	1.57 ± 2.15	**13.02****
N fertilizer (kg N/ha)	153 ± 114	300 ± 153	327 ± 140	**23.92****
P fertilizer (kg P/ha)	13 ± 13	34 ± 39	37 ± 51	5.16
Irrigated area (%) [ha irrigated/total ha]	45% ± 37%	50% ± 36%	31% ± 25%	3.30

Bold values indicate a significant correlation.
* $p \leq .05$.
** $p \leq .01$.

by the two measures. For instance, excessive N fertilizer application could result in excess imported N and in greater GHG emissions. Regardless of degree of association between the measures, both, rather than one, should be used to assess environmental impact on dairy farms, as they measure different sources of environmental impact.

Nitrogen-use efficiencies from other studies on dairy farms in Europe, New Zealand, Australia and USA reportedly range between 8% and 50% (Gourley et al., 2012). The N efficiency range in this study was 9%—76% with an average of 29%. Thus, a higher maximum, but a similar average N-use efficiency, was found in this study when compared with the results of other studies reviewed by Gourley et al. (2012) conducted on commercial dairy farms globally. Similar to this study, wide ranges of P use efficiency have also been found across dairy farms worldwide (Gourley et al., 2012) and the average P use efficiency of 36% found in this study was similar to the average of 32% reported by Gourley et al. (2012) in Australia. Regardless of global comparisons, we found a low nutrient use efficiency, resulting in excessive N and P generated from pasture-based dairy farms in the Eastern Cape. These excess nutrients have the potential to generate negative environmental impacts through build-up in the soil, loss to the atmosphere through volatilization, loss to surface water through run-off, and/or loss to ground water through leaching. Future research should be directed at better understanding the cycling and loss of nutrients on pasture-based dairy farms, so that the environmental impact of these farms can be minimized.

It is more difficult to compare the GHG emissions resulting from pasture-based dairy farms globally, as the methodologies and GHG emission sources included and excluded differ across studies. Despite these limitations, it is interesting to note that the average of 1.39 kg CO_2e/kg ECM was higher than an average of 1.00 kg CO_2e/kg ECM found on New Zealand pasture-based dairy farms (Flysjö et al., 2011). Our findings are also higher than reported by all the studies referenced by de De Léis et al. (2015) in Brazil, New Zealand, Norway, Sweden, Portugal, Spain, Denmark and USA, except for one study in the Netherlands. The estimated emissions for dairy farms in Sub Saharan Africa are 7.5 kg CO_2e/kg FPCM (fat and protein corrected milk, which is a similar calculation to ECM) (Food and Agriculture Organization of the United Nations (FAO), 2010), which is much higher than that found in this study. The main reason for this is that the commercial pasture-based dairy farms included in this study, along with the management practices they implement, are more typical of New Zealand and Australia, rather than representative of Sub Saharan Africa dairy farms. The largest contributor to GHG emissions on these dairy farms was enteric fermentation, a finding established previously, and which this study further supports.

4.2. The association between soil carbon, farm systems, environmental impact and farm management

The main source of N and P imported onto the farms was fertilizer, and therefore the most prominent factor influencing N and P efficiency was fertilizer application rate, as also identified by Fangueiro et al. (2008) and Koesling et al. (2017). Far more N and P were imported onto farms than removed in the milk and animals leaving the farm, indicating that this is not an environmentally efficient system. Practices that could improve the nutrient use efficiencies on these farms are discussed below.

Increased yields on existing, quality agricultural land, along with

Table 5
Farm system descriptors grouped according to total greenhouse gas emissions terciles.

Farm system descriptors	GHG emissions tercile			Kruskal-Wallis H
	Lowest (n = 27)	Middle (n = 26)	Highest (n = 27)	
	Mean ± std deviation			
GHG emissions (kg CO_2e/kg ECM)	1.17 ± 0.09	1.33 ± 0.04	1.66 ± 0.21	
Stocking rate (CiM/ha)	2.27 ± 0.90	3.01 ± 1.42	2.02 ± 1.20	**10.49****
Milk production (kg ECM/cow)	6881 ± 828	6814 ± 821	6398 ± 1006	5.21
Milk production (kg ECM/ha)	15,474 ± 6158	20,128 ± 8508	13,017 ± 7474	**13.41****
Purchased concentrates fed (MJ/kg ECM)	4.54 ± 0.99	4.53 ± 0.92	5.20 ± 1.13	**9.37****
Purchased roughage fed (MJ/kg ECM)	1.25 ± 0.96	2.34 ± 1.61	1.72 ± 2.25	**8.38***
N fertilizer (kg N/ha)	226 ± 130	307 ± 169	247 ± 158	3.65
P fertilizer (kg P/ha)	27 ± 28	33 ± 41	24 ± 47	3.58
Irrigated area (%) [ha irrigated/total ha]	38% ± 27%	59% ± 37%	29% ± 31%	**10.52****

Bold values indicate a significant correlation.
* $p \leq .05$.
** $p \leq .01$.

decreased environmental impacts, are important for achieving agricultural sustainability (Tilman et al., 2002). The most logical approach to mitigating the potential negative environmental impacts associated with dairy farming is therefore to increase farm productivity and efficiency (Capper et al., 2009; Erasmus & Webb, 2013; Guerci et al., 2013; Galloway et al. 2018). An example of this is the association between purchased concentrates fed per milk produced and the environmental impact measures. More efficient feed conversion was associated with higher N use efficiency, and lower GHG emissions. Another example of increased efficiency contributing to reduced environmental impacts is the association of these measures with milk production per hectare. Increased milk production per hectare was associated with higher N use efficiency and lower GHG emissions. Milk production was closely correlated to stocking rate. This association is not surprising as stocking rate and milk production per hectare are positively influenced by various practices which also contribute to higher N use efficiency and lower GHG emissions. These practices, which were not assessed in this study, include rotational grazing management, improved genetic value of cows, increased calving weight of replacement heifers, improved health care of animals and more effective feeding practices (i.e. supplying the correct type and amount of nutrients that the cows need) (Clark et al., 2007; Fangueiro et al., 2008; Capper et al., 2009).

Increased stocking rate and milk production per hectare were associated with higher fertilizer use and a higher portion of farm area being irrigated. Both N fertilizer and irrigation are used as mechanisms to increase pasture growth, thereby increasing the amount of roughage grown per hectare. This increase in pasture roughage supports higher stocking rates, and therefore higher milk production per hectare. Interestingly, the farms in the highest nutrient use efficiency, and lowest GHG emissions tercile had lower stocking density and milk production per hectare than the middle terciles. This indicates that there is a point where production per hectare can be pushed too high, which is not optimal for the goal of reducing environmental impacts.

Scholtz et al. (2013) advocated for increased milk production per cow as a practice to lower GHG emissions per kilogram of milk production. The results of our study concur with their findings. The influence of milk production per cow on GHG emissions intensity is a complex issue though, which is beyond the scope of this study. Our findings are specific to the boundaries, functional units and allocations used. The results should be viewed with this understanding, as Zehetmeier et al. (2012) state, that the variance in GHG emissions relative to milk production per cow is largely influenced by the chosen system boundaries.

When considering both measures of environmental impact, and allowing for NUE and GHG emissions, opportunities to reduce the environmental impact of milk production become apparent. Lower environmental impacts were associated with lower levels of purchased concentrates fed per milk produced. As mentioned above, higher stocking density and milk production per hectare, which were associated with higher N fertilizer application rates, were associated with lower environmental impacts. The farms in the higher NUE and lower GHG emissions terciles had the lowest N fertilizer application rates, but not the lowest stocking densities or milk production per hectare. The farms in the middle GHG emissions tercile had the highest N fertilizer application rates, stocking densities and milk production per hectare. The farms in the middle NUE tercile had the highest stocking densities and milk production per hectare, and the second highest N fertilizer application rates. Farms with the lowest environmental impacts therefore did not have the highest stocking density and milk production. Pasture-based dairy farmers should rather aim to achieve optimal stocking rates and milk production per hectare with minimal use of N and P fertilizer, while limiting the amount of purchased concentrates fed per milk produced. The farm system descriptors for the farms in the highest NUE and lowest GHG emissions terciles show how this has been achieved.

To achieve sustainable agriculture goals, good soil management practices, which result in continuous improvement of soil health and, in turn, increased crop production with the use of less fertilizer per unit of output, need to be adopted (Doran et al., 1996; Hobbs et al., 2008; Zhang et al., 2015). This is how optimal stocking rates with minimal fertilizer inputs, as observed in the lowest environmental impact terciles, can be achieved. The goal of restoring and improving soil health is to produce more from less, which is achieved through the reduction of losses and the improvement of NUE (Lal, 2015). Although fertilizer and manure contribute to improving soil fertility, excessive use can also cause the accumulation of nutrients in the soil, which negatively impacts the environment and animal health (Gourley et al., 2012; Lal, 2015). Fertilizer application on dairy farms should be informed by soil health and fertility testing. Not doing so can prompt excessive and costly nutrients being imported onto a farm. These excessive nutrients do not contribute much to production; rather, they have a negative environmental impact (Lal, 2015). Effective fertilizer management needs to be implemented, i.e. an approach which accounts for N mineralization as a source of inorganic N, and addresses shortages in soil fertility, but does not result in an excess of nutrients being applied (Paustian et al., 2016).

Achieving optimal stocking rates and milk production per hectare while limiting concentrates fed per kilogram ECM milk produced is associated with rotational pasture grazing management, as this results in the effective utilization of pasture grown on the farm (Dillon, 2006; Beukes et al., 2010; Clark et al., 2016). Optimal pasture use lowers purchased feed requirements. Good grazing management also contributes to increased soil C levels, through the input of manure and increased pasture growth (Conant et al., 2001; McSherry & Ritchie, 2013).

A negative correlation was found between soil C levels and GHG emissions, while a positive correlation was found between soil C levels and N-use efficiencies. There is no obvious explanation for the direct driver underlying these associations. The most plausible explanation would be that the management practices which improve soil carbon levels are also part of the drivers minimizing environmental impact. Such practices include planting of perennial grasses, rotational grazing (multi-paddock grazing at a high stocking density with sufficient periods of rest, allowing the pasture to fully recover and grow between grazing events), effective fertilizer management (providing sufficient nutrients without excessive application, especially of N fertilizer) and minimum-tillage (Conant et al., 2001; Hobbs et al., 2008; Teague et al., 2011; Sanderman et al., 2013; Badgery et al., 2014; Rutledge et al., 2015; Clark et al., 2016; Paustian et al., 2016). Farms that had higher soil C levels, also exhibited lower N fertilizer application rates. An opportunity to decrease N fertilizer rates, and thereby increase N use efficiency, thus lies in building soil C levels (Paustian et al., 2016). This is mainly due to C being associated with nutrient cycling and the availability of nutrients, including N, in the soil (Martinez-Salgado et al., 2010; Fageria, 2012).

On pasture-based dairy farms in New Zealand, an average of 115 kg per hectare of N fertilizer is applied per year, with few farms applying more the 250 kg per hectare (Monaghan et al., 2007). In contrast, an average of > 240 kg per hectare of N fertilizer was applied on the pasture-based dairy farms in the Eastern Cape, South Africa. Although a direct comparison is unfair due to the differences in climate and soil type (New Zealand has high rainfall and volcanic soils, so higher leaching could actually be expected), this large difference, along with the average of 130 kg of N fertilizer achieved by the farms in the highest NUE tercile, indicates that the pasture-based dairy farms which apply large amounts of N fertilizer (> 250 kg N/ha/year) should be able to reduce their fertilizer application rates per unit of output. A possible influence of New Zealand having lower fertilizer application rates is that this is that they have stringent environmental monitoring, ensuring farms stick to regulations (Monaghan et al. 2007). Ecological intensification has been proposed as a method to create a sustainable farm system (Bender et al., 2016). By optimizing the role played by soil biota in nutrient and carbon cycling, a system which is characterized by moderate resource inputs, internal regulatory processes and low nutrient loss can result in high productivity (Bender et al., 2016). The actual mechanics of the loss of N and P from dairy pastures, and ways of mitigating this, have been widely researched globally (Monaghan et al., 2007) and are beyond the scope of this study. Further research in the South African context would contribute to helping farmers improve the NUE on their farms.

5. Conclusion

Sustainability indicators such as a carbon footprint calculator and a nutrient budget allow for the assessment of environmental impacts of dairy farming. This research provides insight into the NUE and GHG emissions resulting from current farming systems in the Eastern Cape, South Africa. The methods used in this research, and insights gained are of interest to pasture-based dairy farming throughout the world. The results show that the South African context is more comparable to New Zealnd and Australia. South Africa should not be grouped into Sub Saharan Africa when assessing the environmental impact of dairy farming, especially when developing benchmarks. The farm system adopted on pasture-based dairy farms influences the environmental impact of that farm. The opportunity exists on pasture-based dairy farms to reduce the environmental impact of milk production by optimizing production on the available land, while not over-applying fertilizer or feeding an excessive amount of purchased feeds. The two practices that contribute to achieving this are sustainable soil management and rotational grazing management.

Acknowledgements

The authors are appreciative of the help of Phillip and Marlene Terblanche, owners of Trace & Save, in terms of providing intellectual guidance, support and insight to the dairy industry. This work was supported by Woodlands Dairy and Trace & Save.

References

Badgery, W.B., Simmons, A.T., Murphy, B.W., Rawson, A., Andersson, K.O., Lonergan, V.E., 2014. The influence of land use and management on soil C levels for crop-pasture systems in Central New South Wales, Australia. Agric. Ecosyst. Environ. 196, 147–157.

Bender, S.F., Wagg, C., Van Der Heijden, M.G., 2016. An underground revolution: biodiversity and soil ecological engineering for agricultural sustainability. Trends Ecol. Evol. 31 (6), 440–452.

Beukes, P.C., Gregorini, P., Romera, A.J., Levy, G., Waghorn, G.C., 2010. Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. Agric. Ecosyst. Environ. 136 (3), 358–365.

Bryman, A., 2012. Social Research Methods, 4th ed. Oxford University Press.

Capper, J.L., Cady, R.A., Bauman, D.E., 2009. The environmental impact of dairy production: 1944 compared with 2007. J. Anim. Sci. 87 (6), 2160–2167.

Cichota, R., Snow, V.O., 2009. Estimating nutrient loss to waterways-an overview of models of relevance to New Zealand pastoral farms. N. Z. J. Agric. Res. 52 (3), 239–260.

Clark, D.A., Caradus, J.R., Monaghan, R.M., Sharp, P., Thorrold, B.S., 2007. Issues and options for future dairy farming in New Zealand. N. Z. J. Agric. Res. 50 (2), 203–321.

Clark, C.E., Fariῆa, S.R., Garcia, S.C., Islam, M.R., Kerrisk, K.L., Fulkerson, W.J., 2016. A comparison of conventional and automatic milking system pasture utilization and pre- and post-grazing pasture mass. Grass Forage Sci. 71 (1), 153–159.

Conant, R.T., Paustian, K., Elliott, E.T., 2001. Grassland management and conversion into grassland: effects on soil C. Ecol. Appl. 11 (2), 343–355.

De Léis, C.M., Cherubini, E., Ruviaro, C.F., Da Silva, V.P., Do Nascimento Lampert, V., Spies, A., Soares, S.R., 2015. Carbon footprint of milk production in Brazil: a comparative case study. Int. J. Life Cycle Assess. 20 (1), 46–60.

Dillon, P., 2006. Achieving high dry-matter intake from pasture with grazing dairy cows. In: Elgersma, A., Dijkstra, J., Tamminga, S. (Eds.), Fresh Herbage for Dairy Cattle. Springer, Netherlands, pp. 1–26.

Doran, J.W., 2002. Soil health and global sustainability: translating science into practice. Agric. Ecosyst. Environ. 88 (2), 119–127.

Doran, J.W., Sarrantonio, M., Liebig, M.A., 1996. Soil health and sustainability. Adv. Agron. 56, 1–54.

Dou, Z., Galligan, D.T., Ramberg, C.F., Meadows, C., Ferguson, J.D., 2001. A survey of dairy farming in Pennsylvania: nutrient management practices and implications. J. Dairy Sci. 84, 966–973.

Eisenhauer, N., Antunes, P.M., Bennett, A.E., Birkhofer, K., Bissett, A., Bowker, M.A., Caruso, T., Chen, B., Coleman, D.C., De Boer, W., De Ruiter, P., 2017. Priorities for research in soil ecology. J. Soil Ecol. 63, 1–7.

Erasmus, L.J., Webb, E.C., 2013. The effect of production system and management practices on the environmental impact, quality and safety of milk and dairy products. S. Afr. J. Anim. Sci. 43 (3), 424–434.

Fageria, N.K., 2012. Role of soil organic matter in maintaining sustainability of cropping systems. Commun. Soil Sci. Plant Anal. 43 (16), 2063–2113.

Fangueiro, D., Pereira, J., Coutinho, J., Moreira, N., Trindade, H., 2008. NPK farm-gate nutrient balances in dairy farms from Northwest Portugal. Eur. J. Agron. 28 (4), 625–634.

Flysjö, A., Henriksson, M., Cederberg, C., Ledgard, S., Englund, J.E., 2011. The impact of various parameters on the Carbon footprint of milk production in New Zealand and Sweden. Agric. Syst. 104 (6), 459–469.

Food and Agriculture Organization of the United Nations (FAO), 2010. Greenhouse gas emissions from the dairy sector. A life cycle assessment. In: Report: Animal Production and Health Division. FAO, Rome, Italy.

Food and Agriculture Organization of the United Nations (FAO), 2017. Soil Organic Carbon: The Hidden Potential. FAO, Rome, Italy.

Galloway, C., Conradie, B., Prozesky, H., Esler, K., 2018. Are private and social goals aligned in pasture-based dairy production? J. Clean. Prod. 175, 402–408.

Gourley, C.J., Dougherty, W.J., Weaver, D.M., Aarons, S.R., Awty, I.M., Gibson, D.M., Hannah, M.C., Smith, A.P., Peverill, K.I., 2012. Farm-scale nitrogen, phosphorus, potassium and sulfur balances and use efficiencies on Australian dairy farms. Anim. Prod. Sci. 52 (10), 929–944.

Guerci, M., Bava, L., Zucali, M., Sandrucci, A., Penati, C., Tamburini, A., 2013. Effect of farming strategies on environmental impact of intensive dairy farms in Italy. J. Dairy Res. 80 (3), 300–308.

Halberg, N., Verschuur, G., Goodlass, G., 2005. Farm level environmental indicators; are they useful? An overview of green accounting systems for European farms. Agric. Ecosyst. Environ. 105 (1), 195–212.

Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. B 363 (1491), 543–555.

International Panel on Climate Change (IPCC), 2006a. Guidelines for national greenhouse gas inventories. Chapter 10: Emissions from livestock and manure management. In: Agriculture, Forestry and Other Land Use. vol. 4.

International Panel on Climate Change (IPCC), 2006b. Guidelines for national greenhouse gas inventories. Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. In: Agriculture, Forestry and Other Land Use. vol. 4.

Koesling, M., Hansen, S., Bleken, M.A., 2017. Variations in nitrogen utilisation on conventional and organic dairy farms in Norway. Agric. Syst. 157, 11–21.

Lal, R., 2015. Restoring soil quality to mitigate soil degradation. Sustainability 7 (5), 5875–5895.

Langeveld, J.W., Verhagen, A., Neeteson, J.J., Van Keulen, H., Conijn, J.G., Schils, R.L., Oenema, J., 2007. Evaluating farm performance using agri-environmental indicators: recent experiences for nitrogen management in The Netherlands. J. Environ. Manag. 82 (3), 363–876.

Martinez-Salgado, M.M., Gutierrez-Romero, V., Jannsens, M., Ortega-Blu, R., 2010. Biological soil quality indicators: a review. In: Mendez-Vilas (Ed.), Current Research, Technology and Education Topics in Applied Microbiology and Microbial Biotechnology. Formatex, pp. 319–328.

McSherry, M.E., Ritchie, M.E., 2013. Effects of grazing on grassland soil carbon: a global review. Glob. Chang. Biol. 19 (5), 1347–1357.

Middelberg, S.L., 2013. Sustainable agriculture: a review of challenges facing the South African agricultural sector. J. Hum. Ecol. 42 (2), 163–169.

Monaghan, R.M., Hedley, M.J., Di, H.J., McDowell, R.W., Cameron, K.C., Ledgard, S.F., 2007. Nutrient management in New Zealand pastures - recent developments and future issues. N. Z. J. Agric. Res. 50, 181–201.

Mu, W., Groen, E.A., van Middelaar, C.E., Bokkers, E.A.M., Hennart, S., Stilmant, D., de Boer, I.J.M., 2017. Benchmarking nutrient use efficiency of dairy farms: the effect of epistemic uncertainty. Agric. Syst. 156, 25–33.

Non-Affiliated Soil Analysis Work Committee, 1990. Handbook of Standard Soil Testing Methods for Advisory Purposes. Soil Science Society of South Africa, Pretoria.

O'Brien, D., Capper, J.L., Garnsworthy, P.C., Grainger, C., Shalloo, L., 2014. A case study of the carbon footprint of milk from high-performing confinement and grass-based dairy farms. J. Dairy Sci. 97 (3), 1835–1851.

Oenema, O., Boers, P.C., Van Eerdt, M.M., Fraters, B., Van Der Meer, H.G., Roest, C.W., Schröder, J.J., Willems, W.J., 1998. Leaching of nitrate from agriculture to groundwater: the effect of policies and measures in the Netherlands. Environ. Pollut. 102(1, 471–478.

Oenema, O., Kros, H., de Vries, W., 2003. Leaching of nitrate from agriculture to groundwater: the effect of policies and measures in the Netherlands. Eur. J. Agron. 20, 3–16.

Ondersteijn, C.J., Beldman, A.C., Daatselaar, C.H., Giesen, G.W., Huirne, R.B., 2002. The Dutch mineral accounting system and the European nitrate directive: implications for N and P management and farm performance. Agric. Ecosyst. Environ. 92 (2), 283–296.

Parr, J.F., Papendick, R.I., Hornick, S.B., Meyer, R.E., 1992. Soil quality: attributes and relationship to alternative and sustainable agriculture. Am. J. Altern. Agric. 7 (1–2), 5–11.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532 (7597), 49–57.

Pérez Urdiales, M.P., Lansink, A.O., Wall, A., 2016. Eco-efficiency among dairy farmers: the importance of socio-economic characteristics and farmer attitudes. Environ. Resour. Econ. 64 (4), 559–574.

Rigby, D., Woodhouse, P., Young, T., Burton, M., 2001. Constructing a farm level

indicator of sustainable agricultural practice. Ecol. Econ. 39, 463–478.
Rotz, C.A., Montes, F., Chianese, D.S., 2010. The Carbon footprint of dairy production systems through partial life cycle assessment. J. Dairy Sci. 93 (3), 1266–1282.
Rutledge, S., Mudge, P.L., Campbell, D.I., Woodward, S.L., Goodrich, J.P., Wall, A.M., Kirschbaum, M.U., Schipper, L.A., 2015. C balance of an intensively grazed temperate dairy pasture over four years. Agric. Ecosyst. Environ. 206, 10–20.
Sanderman, J., Fillery, I.R., Jongepier, R., Massalsky, A., Roper, M.M., Macdonald, L.M., Maddern, T., Murphy, D.V., Wilson, B.R., Baldock, J.A., 2013. C sequestration under subtropical perennial pastures I: overall trends. Soil Res. 51 (8), 760–770.
Scholtz, M.M., Van Ryssen, J.B., Meissner, H.H., Laker, M.C., 2013. A south African perspective on livestock production in relation to greenhouse gases and water usage. S. Afr. J. Anim. Sci. 43 (3), 247–254.
Sjaunja LO, Baevre L, Junkkarinen L, Pedersen J & Setälä J. 1990. A nordic proposal for an Energy Corrected Milk (ECM) formula. 27th Session International Committee for Recording and Productivity of Milk Animals. July 2–6, 1990, Paris, France.
Spears, R.A., Kohn, R.A., Young, A.J., 2003. Whole-farm nitrogen balance on western dairy farms. J. Dairy Sci. 86, 4178–4186.
Teague, W.R., Dowhower, S.L., Baker, S.A., Haile, N., Delaune, P.B., Conover, D.M., 2011. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agric. Ecosyst. Environ. 141 (3), 310–322.
Thomassen, M.A., De Boer, I.J., 2005. Evaluation of indicators to assess the environmental impact of dairy production systems. Agric. Ecosyst. Environ. 111 (1), 185–199.
Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418 (6898), 671–677.
United Kingdom Department of Environment, Food and Rural Affairs (DEFRA), Department of Energy and Climate Change (DECC), 2012. Guidelines to DEFRA/DECC's GHG Conversion Factors for Company Reporting.
Van Calker, K.J., Berentsen, P.B.M., Giesen, G.W.J., Huirne, R.B.M., 2005. Identifying and ranking attributes that determine sustainability in Dutch dairy farming. Agric. Hum. Values 22 (3), 53–63.
Van Tonder, C., Hillier, J., 2014. Cool Farm Tool. Technical Documentation for the Online Cool Farm Tool. Cool Farm Alliance. https://www.coolfarmtool.org/.
Zehetmeier, M., Baudracco, J., Hoffmann, H., Heißenhuber, A., 2012. Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach. Animal 6 (1), 154–166.
Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nature 528 (7580), 51–59.