frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 29 October 2024
DOI 10.3389/fsufs.2024.1397305

OPEN ACCESS

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RECEIVED 07 March 2024
ACCEPTED 07 October 2024
PUBLISHED 29 October 2024

CITATION
Reinecke R, Blignaut JN, Meissner HH and Swanepoel PA (2024) Advancing carbon sequestration and nutrient management in the South African dairy industry for sustainable growth.
Front. Sustain. Food Syst. 8:1397305.
doi: 10.3389/fsufs.2024.1397305

Advancing carbon sequestration and nutrient management in the South African dairy industry for sustainable growth

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The dairy industry in South Africa is currently grappling with significant challenges, including escalating costs and diminishing profit margins. However, these difficulties also create a pivotal opportunity for the sector to embrace sustainable practices that not only enhance environmental stewardship but also encourage economic resilience. A crucial step in this transition is to dispel prevalent misconceptions about the industry's environmental footprint and to highlight its positive contributions to sustainable agricultural practices. Farmers are encouraged to adopt innovative strategies that enhance soil health and reduce their ecological impact. This review focuses on essential factors influencing nutrient management and the processes that contribute to soil carbon enhancement. Effective management is crucial for the sustainability of pasture-based dairy systems, as herbage biomass significantly influences nutrient cycling and soil organic matter accumulation. For instance, well-managed pastures with high biomass can efficiently recycle nutrients from manure, enhancing plant growth. This process contributes to soil organic carbon buildup, which aids in carbon sequestration. In contrast, poor nutrient management can lead to nutrient imbalances and lower herbage production, reducing carbon storage potential. Moreover, the movement of nutrients below the surface is a critical pathway for enhancing soil health and promoting ecological balance. By implementing sustainable practices and refining nutrient stewardship strategies, pasture-based dairy farmers can significantly advance their sustainability goals. This includes recognizing the broader implications of soil health on farm productivity and environmental resilience, as well as the potential for improved biodiversity.

KEYWORDS

carbon sequestration, greenhouse gas emissions, dairy industry, consumer demands, environmental impact

1 Introduction

Most efforts in the dairy sector in recent years to adapt to climate change focused on mitigation strategies. However, it is increasingly clear that C sequestration offers not only emission mitigation but also additional co-benefits, surpassing the potential of other approaches (Harrison et al., 2021). Given the variation between South African dairy farms due to the different management strategies applied, variations in climatic regions, the availability of resources, and the complexity of dairy farming, many opportunities exist to mitigate greenhouse gas (GHG) emissions (Reinecke and Casey, 2017) and incorporate carbon sequestration strategies. The livestock sector in general, and the dairy industry specifically, has recently come under pressure from climate change activists concerning the GHG emissions attributed to the enteric fermentation in the animal sector. The pressure has mounted to the level that the collapse of the global livestock sector is predicted (Tubb and Seba, 2021). The mounting impact of consumer concerns could negatively impact the dairy sector if the consumer is not properly informed, and if the data is not publicly recognised. This could also result in the unnecessary contraction of the industry as a result of decreased demand in the animal food sector, potentially exacerbating the already stressed supply chain and threatening food security. It is of critical importance to have valid information on the impact of any agricultural practices before generalisations can be made about any single food commodity regarding its environmental footprint.

In addition to the concerns related to climate change, the South African dairy industry is facing significant challenges related to rising costs and declining profits on farms, according to the latest Lacto Data report from Milk SA. The number of milk producers in South Africa decreased from 891 in January 2023 to 882 in January 2024, a 1.0% decline (Milk SA, 2024). This reduction reflects the difficulties faced by smaller operations in maintaining viability in a competitive market. Despite a slight increase in production per producer up 52% from 2,499 tons in 2018 to 3,786 tons in 2023, the total milk production has decreased by 2.1%, from 3,411,000 tons in 2018 to 3,339,000 tons in 2023 (Milk SA, 2024). This indicates that while larger farms may be becoming more efficient, the overall industry is contracting due to the challenges faced by producers. One of the primary drivers of the decline in profitability is the sharp increase in input costs. The Milk Producers' Organisation (MPO) reports that while milk producers received price increases in 2022 and 2023, the overall profitability of dairy farming remains precarious due to the escalating costs of feed, fuel, and labor [Milk Producers' Organisation (MPO), 2023]. Statistics indicate that the price of fresh milk at the factory level decreased by 3.8% from September 2022 to September 2023, while the price of UHT milk increased by 6.9% (Milk SA, 2024). This disparity highlights the challenges faced by milk processors, who are not benefiting from the higher retail prices, thus squeezing their margins further. The economic strain on dairy farmers is further exacerbated by a decline in consumer demand. In 2023, retail sales of various dairy products, along with unprocessed milk, decreased due to widespread price hikes in consumer goods and services, compounded by slow economic growth (Milk SA, 2024). South Africa's GDP (at 2015 prices and annualised) value was 0.6% higher in 2023 than in 2022, but the recovery was contracted and hampered by major disruptions in the supply of electricity and poor service delivery by the public sector (Milk SA, 2024). The combination of high operational expenses, decreased consumer demand, and external market pressures highlights the urgent need for strategic interventions to support the sustainability and profitability of the dairy sector in South Africa. The growing awareness and concerns surrounding the impact of GHG emissions originating from livestock agriculture have resulted in many assumptions and misinterpretations being made (Liu et al., 2021). Among these are the lifecycle of methane (CH_4) in the atmosphere, the impact of the accumulated degrading biomass left from crop agriculture (not intended as animal feed), and the overestimation of this emission in the animal sector at a global level. For instance, many stakeholders often perceive dairy farming as a leading contributor to greenhouse gas emissions without recognizing the nuances of its environmental footprint. Research indicates that while dairy production does contribute to emissions, advancements in management practices, such as improved feed efficiency and manure management, can significantly mitigate these impacts. For example, a study by the Food and Agriculture Organization (FAO) highlights that optimizing dairy production systems can reduce methane emissions by up to 30% per unit of milk produced (Gerber et al., 2013).

It is imperative to accurately determine the degree of emissions generated across the food value chain to better identify GHG emissions sources in the food system, starting at a local level. Such as the business case report by the WWF-SA (2021), which emphasizes that implementing sustainable practices in dairy production can lead to significant environmental benefits. The report suggests that if best management practices are adopted across dairy farms in regions like the Eastern Cape and KwaZulu-Natal, it could result in a 10% reduction in carbon emissions and 27% reduction in excess nitrogen. This showcases that misconceptions about dairy's negative environmental impact can be countered by evidence of sustainable practices leading to both environmental and economic benefits. Efforts to decrease emission intensity should prioritize developing countries with the largest mitigation potential, as enhancing production efficiency yields a more significant impact than demand-side strategies. In this context, China, India, and South Africa are identified as the three countries with the greatest mitigation potential. For instance, China's emissions intensity declined from 1.07 kg CO_2 per USD in 2007 to 0.69 kg CO_2 in 2017, reflecting substantial improvements in production efficiency. Similarly, India experienced a decrease in emission intensity by 19% after 2011, bringing it down to 0.92 kg CO_2 USD in 2017, although it remains higher than China's. South Africa, while not specified in the same detail, faces similar challenges and opportunities, with agriculture contributing approximately 14% to its total greenhouse gas emissions. By focusing on improving production efficiency in these countries, significant reductions in overall emissions can be achieved, thereby supporting global climate goals (Chang et al., 2021; UNCTAD, 2023).

Consumers' demands stem from their respective choices, beliefs and backgrounds. A recent trend in consumer demand relates to the concerns around carbon emissions generated by agriculture, more specifically the livestock sector, which has greatly impacted consumer behaviour following a report by Willett et al. (2019). This report encourages the consumption of more plant-based diets in efforts to mitigate carbon emissions and lessen the impact on the environment. Greater interest in plant-based alternatives to meat and dairy has increased the popularity of plant-based imitation dairy products. Some of the most popular plant-based beverages available in South Africa include soy, oat and almond milk. These products are marketed as being better for the environment as opposed to milk. The rationale stems from a FAO report, entitled *Livestock's Long Shadow*, which estimated that 18% of anthropogenic greenhouse gasses were attributed to the livestock sector (FAO, 2006). This figure has since been recalculated to 14.5% (Grossi et al., 2019). It is imperative to emphasise that all agricultural processes invariably exert a negative impact on the environment, and a comprehensive, equitable assessment is essential. Such an evaluation should encompass the entire agricultural system rather than solely focusing on the environmental impact of the end product.

Animals play an important socio-economic role in South Africa, providing both financial and nutritional stability to many households and industries (MacLaren et al., 2019). The animal sector, and in particular dairy cattle, can use nutrient-poor crops and plant materials that are not suited for human consumption. These animals can convert these nutrient-lacking foodstuffs into nutrient-dense foodstuffs such as milk and meat. It is also worth mentioning that the entire animal can be used to sustain and nurture human life, whereas a large portion of plant material remains relatively unused in many crops. In many annual crops, the plant material (biomass) that is not suitable for human consumption, is left to naturally decompose which would also contribute to GHG emissions under anaerobic conditions. Another important consideration is that crop production, especially where synthetic fertiliser is applied, can lead to higher emissions, whereas the incorporation of animals into agricultural systems can offer opportunities for improved nutrient cycling, reduced reliance on synthetic fertilisers, and enhanced soil health (Smit E. H. et al., 2021). More focus should be on soil carbon sequestration potential, as grazed pastures can be substantial carbon sinks. The nutritional value of animal foods cannot be discredited or understated in a country where undernutrition and malnutrition are still prevalent.

Consequently, this review article will discuss the key elements that form part of the on-farm net GHGs originating from pasture-based dairy cattle, their products, as well as aboveground and belowground sources. This review is intended to provide insights for the dairy industry in addressing evolving consumer demands and perceptions related to the industry's environmental impact.

2 Addressing key industry concerns through research and practical solutions

Understanding the effect on net GHG from a farm and its key environmental indicators, the industry would be enabled to:

- offer science-backed and informed claims about its carbon footprint and by extension its nutritional footprint in South Africa;
- support and influence stakeholder and client perception that drives market behaviour;
- address the sector's environmental footprint—where action needs to be implemented through informed decisions towards land-use and production changes without compromising profitability; and
- monitor any possible onsite environmental impacts, and expressing such in monetary terms, and taking precautionary and mitigating adaptive steps.

Accordingly, further research is critical to develop a practical tool that will assist dairy farmers in adopting the best animal and land use management practices from the outset—thus advancing competitiveness and sustainability and reducing the risk of failure. Such research should support initiatives to determine the economic and environmental impact of dairy production in South Africa, focusing on the total estimation of carbon capturing and storage capacity included in the on-farm dairy production systems. Emphasis should be on all the critical nutrient flows that impact the system and thereby determine if a farm is a carbon emission source or a sink.

The environmental footprint of the dairy sector originates from GHG emissions, the release of N into the water and the atmosphere, as well as converting land into pasture grazing. Currently, the situation on most pasture-based dairy farms is that the environmental impact of farms is not adequately monitored, even though it has a critical impact on production cost and profitability. Improved and suitable management strategies are also needed to prevent soil degradation and reduced fertility in cultivated pastures. Swanepoel et al. (2015) reported that monitoring of environmental indicators on farms is often driven by outdated research or increased sales performances from service providers, rather than being aligned with results from soil tests. This can often lead to a decrease in soil fertility, such as lower soil organic C. However, due to difficulty in monitoring processes and the application of stricter fertiliser guidelines which are aligned with nutrient build-up in the soil, the decision-making processes are not always applied for reducing the environmental footprint, increasing profitability and reducing the sector's reputational risk.

The cumulative net GHG emission intensity relative to the cumulative amount of meat and milk produced will vary among individual cows and between herds and farms. This should be referred to as the net GHG emission or sink. Depending on input parameter values, several scenarios can provide a range of outcomes. These inputs will be impacted by differences in the metabolisable energy requirements of cows, which will vary depending on their physiological status where factors such as pregnancy, growth, weight, and milk production play a key role. Such a complex system to estimate carbon sequestration and the role of cows as biogenic sources of carbon will include many variables and needs to be included in a multifactorial monitoring tool.

3 Methods

A rigorous methodology was employed to select the most relevant indicators to provide a comprehensive understanding of the environmental impacts of pasture dairy farms while also considering the economic effects of sustainability practices. By utilizing established guidelines and selecting relevant indicators supported by quantitative data from the literature, the review will contribute valuable insights into improving the sustainability of dairy farming in South Africa. This process involved utilizing established guidelines and frameworks to ensure that the chosen indicators comprehensively reflect the environmental and economic dimensions of dairy farming.

The first step in the review process involved identifying recognized guidelines for environmental assessments, such as the Life Cycle Assessment framework and the Sustainable Development Goal. These frameworks provide a structured approach to evaluating the environmental impacts associated with agricultural practices. Specifically, the LCA methodology was applied to assess the carbon footprint and resource use of pasture-based dairy systems, as highlighted in recent studies, including those focusing on South African dairy farms. To select the most pertinent indicators, a omprehensive literature search was conducted using databases such as Google Scholar, ScienceDirect, and MDPI. Papers were selected based on their relevance to the chosen indicators, with a particular emphasis on studies that provided empirical data from South African dairy farms.

The selection criteria for the papers focused on relevance and preference was given to studies that provided quantitative assessments of environmental impacts, such as greenhouse gas emissions, nutrient runoff, and resource consumption. Studies that included data from South Africa were prioritized to ensure the review's applicability to local conditions. Several key studies were identified that supported the chosen indicators. For example, a study by Smit E. H. et al. (2021) assessed the environmental impact of rotationally grazed pastures in South Africa, providing valuable data on carbon sequestration and nutrient management practices. Another relevant study by Musto et al. (2023) compared regenerative and conservation agriculture practices, highlighting their effects on soil quality and farm economics, which is crucial for understanding the economic implications of sustainability

4 Nutrient cycling in cattle

Cows, often referred to as carbon recyclers, produce biogenic carbons that are collected, stored and discharged through organic material (Lean and Moate, 2021). In the process of converting non-human-consumable plants into animal products, dairy cows emit methane (CH_4). This CH_4 can be effectively converted back into carbon dioxide through hydroxyl oxidation and subsequently absorbed by plants, thereby completing the cycle (Blignaut et al., 2022). Therefore, this research suggests that livestock may also act as an emission sink, not just a source. Furthermore, the biogenic carbon cycle is shorter-lived than carbon released from fossil fuels, which can take years to redeposit due to being geologically trapped in deep soils (Lynch et al., 2020).

According to Charmley et al. (2016), CH_4 emissions indicate an unproductive use of dietary energy, as it represents a loss of carbon. Calorimetry trials conducted on a diverse range of forages and forages with supplements suggested that CH_4 production at 6.3% of gross energy intake is significantly lower than previously accepted. This indicates that feed digestibility has improved, resulting in lower CH_4 emissions. As such, fermentation stoichiometry is crucial in predicting energy and nutrient utilisation and environmental impact. By considering the carbohydrate fermentation pathway, we can estimate the available energy-yielding substrate for the animal and determine critical factors in methanogenesis.

The microbiota in the rumen carries out the important task of metabolising monosaccharides from complex carbohydrates and starch through the glycolytic pathway, resulting in the formation of three primary volatile fatty acids, namely acetate, propionate and butyrate (Ungerfeld, 2020). Hemicelluloses, which are abundant in plants and contain pentoses, are metabolised via the pentose cycle, leading to the production of acetate and ribose 5-phosphate (Hackmann et al., 2017). Overall, the natural byproducts of microbial fermentation in the rumen comprise volatile fatty acids, CH_4 and CO_2.

The ratio of volatile fatty acids, namely the ratio of lipogenic (mainly acetate and butyrate) and glucogenic (mainly propionate) has a fundamental influence on methanogenesis in the rumen. The practical implication when shifting the ratios of volatile fatty acids formation can be seen in the acrylate pathway when propionate formation may increase in high-concentrate diets. A minor volatile fatty acid, valerate, formed in the carbohydrate metabolism process, can also be a net sink for reducing CH_4 because it slightly reduces H_2 production (Hristov et al., 2013; Knapp et al., 2014).

Reducing emissions from enteric CH_4 while improving animal productivity and feed efficiency is possible through nutritional strategies and manipulation. By altering the metabolic pathways of rumen fermentation through different feed additives, we can achieve different outcomes, including reducing CH_4 emissions. Nutritional strategies involve changing forage quality and quantity or supplementing feed additives that inhibit methanogenesis or alter metabolic pathways. The chemical composition of feed ingredients, particularly carbohydrates and protein, can have a significant impact on emission outcomes. Predicting the carbohydrate fermentation pathway is crucial in estimating the type of energy-yielding substrate available to the animal, and the ratio of lipogenic to glucogenic volatile fatty acids is a key determinant of methanogenesis (Hristov et al., 2013; Knapp et al., 2014).

Over the past few decades, researchers have studied how dietary changes can help reduce CH_4 emissions from livestock, which could be incorporated into farming practices by using feed additives (Cottle et al., 2016). New insights into CH_4 production have led to the discovery of feed additives that can reduce CH_4 emissions in varying degrees. Some of these additives could help make animal-sourced foods more sustainable by significantly reducing CH_4 emissions. For example, certain feed additives can inhibit CH_4 production or compete with methanogens for food, such as 3-nitroxypropanol (3NOP) which has been shown to reduce enteric methane emissions in dairy cows by up to 30% and in beef cattle by as much as 45% (Uddin et al., 2022) In contrast, Feng and Kebreab (2020) found that nitrates can reduce CH_4 emissions with 30% by competing with methanogens for hydrogen, while Van Wyngaard et al. (2018) found that although nitrate reduced CH_4 emissions effectively, it compromised dry matter intake (DMI) from concentrate feed by approximately 10% and total milk production by around 5%. Other feed additives include lipids, plant secondary compounds and essential oils. Of these, lipids have been studied extensively, but while supplementing with medium-chain and polyunsaturated fatty acids can reduce CH_4 production by 10% in livestock, results have varied (Beauchemin et al., 2008). Similarly, secondary plant compounds and essential oils have shown inconsistent results, sometimes with substantial reduction but sometimes with a modest increase in CH_4 emissions.

Increasing digestibility and ruminal passage rate through particle size reduction and food processing can alter microbial populations and volatile fatty acid production by shifting some digestion to the intestines. Owing to compromised rumen health or insufficient ration formulation or feed processing, situations exist where dry matter intake is depressed and digestion is not optimal—resulting in lower milk production and poor feed efficiency.

Various animal factors can contribute to both sources and sinks of emissions. Studies have shown there are no significant variations in GHG between breeds, but rather differences between individual animals because of different feed intake levels and variations in milk production and milk quality. Since CH_4 production is proportional to dry matter intake, it is suggested to effectively determine differences in emission production potential within animals, the residual feed intake (RFI) is a more effective method of measure (Basarab et al., 2013). Feed efficiency can be determined through residual feed index or its components, such as body weight, milk production and composition, and dry matter intake. The RFI is the difference between an animal's actual feed intake and expected feed intake over a specific period, and is an indicator of feed efficiency. Lower RFI in dairy cows can lower methane production and improve milk production efficiency. Animals with high reproductive performance and a high fertility rate can add to less need for replacement heifers, thus less unproductive animals, and a reduction in replacement rate, all of which mean more productive cows can be kept on the farm, and in turn indirectly lower emissions on the farm, especially when it is expressed per unit of final product.

5 C and N flow in the aboveground pool

To effectively reduce GHG emissions from livestock, it is critical to consider the full cycle and make provision for any trade-offs within the system. During grazing, herbivores disconnect the N from C by naturally consuming portions highest in N concentration. From the ingested pasture, only a small fraction of C, typically around 5–10%, is retained in the meat (Adler et al., 2013); however, in intensive dairy production, the fraction of ingested C retained in milk can reach 20% (Faverdin et al., 2007). There is about 70–80% of N that will be excreted into the soil via urine and faeces. Livestock has been shown to have different conversion efficiencies, depending on the farm management system, physiological condition of the animal, and type of feed, among others (Bouwman et al., 2002). The effect of feed composition on milk production needs to be considered in the development of a balanced feeding strategy as the available nutrients included in the given diet will eventually impact into final products.

The excretion rate of nitrogen (N) is a critical aspect of any pasture-based dairy production system. Inorganic N enters the system primarily through fertiliser application, while biological N results from animal waste and organic matter decomposition. Careful monitoring and comprehension of this N flow is essential for optimal management of the dairy operation.

Another important emission source from dairy farms is manure. How manure is handled and utilised on these farms can contribute to the emission of GHG such as CH_4 and N_2O particularly in the case of liquid manure (Uddin et al., 2022). Manure management systems therefore determine the combined process of nitrification and denitrification which results in the production of direct and indirect emissions of N_2O in the animal waste system. Increased aeration initiates nitrification–denitrification reactions, facilitating the release of N2O. Consequently, higher production rates of N2O are expected with increased aeration, with emissions increasing by up to 80% (Mosier et al., 1998).

Another source of CH_4 emissions that is associated with manure management, refers to manure accumulation, storage, processing and application to crops (IPCC, 2019). When manure is handled as a solid or deposited to pastures, it decomposes mostly under aerobic conditions, whereas manure handled as slurry decomposes in an anaerobic manner, producing significantly higher amounts of CH_4, up to 20 times more, compared to aerobic decomposition of manure (Baral et al., 2018). Hence, the reduction of CH_4 emissions from manure handling should focus on preventing anaerobic conditions during the storage of manure.

There are several factors that all play a part in the amount of CH_4 produced from manure. The specific composition of manure, which greatly depends on the composition and digestibility of the animal diet, as well as climate affects the amount of CH_4 produced (Dalby et al., 2021). Except for oxygen availability discussed above, water content, pH and nutrient availability have an impact on manure CH_4 production. Therefore, optimal conditions for CH_4 production include an anaerobic water-based environment, a high level of nutrients for bacterial growth, a neutral pH (close to 7.0), warm temperatures, and a moist climate.

Methane generation normally takes place in the volatile solids portion of the manure. Improvements in the digestibility of animal feeds associated with high-yielding dairy production systems increase the proportion of volatile solids available in manure and in return, increase CH_4 production on a per animal basis. Additionally, animal type and diet also affect the quantity of CH_4 produced per kg of volatile solids in the manure (IPCC, 2019).

Dairy manure is a valuable source of carbon that can be sequestered over the long term, depending on management practices and the digestibility of the feed. The effectiveness of C sequestration in manure is influenced by various manure management systems, including composting, anaerobic digestion, and direct application to soil. For instance, biochar-composting has been shown to reduce methane emissions by 79% compared to traditional composting methods, while also enhancing C sequestration potential (Uddin et al., 2022). Globally, dairy manure management practices vary widely, with intensive dairy systems often relying on liquid manure management, which can contribute significantly to GHG emissions. In fact, intensive dairy operations can account for up to 50% of livestock methane emissions (Mosier et al., 1998). The C content sequestered from manure is not exclusive to intensive dairy systems; extensive systems can also contribute to carbon sequestration, albeit at different rates. For example, a meta-analysis of Manure Application reviewed 101 studies and found that manure application increased soil organic C stocks by an average of 10.7 tonnes per hectare across various conditions, which suggests that manure significantly enhances carbon sequestration in soils (Rome Gross and Glaser, 2021). Overall, the potential for C sequestration from dairy manure management is substantial, but it requires the adoption of effective practices tailored to the specific conditions of each farm system.

At the same time animals, mostly on pasture, recycle nutrients through urine and manure excretion, which enhance the biological cycle of nutrients such as N, P and K, which bound organic C. This process is known as decoupling and mineralisation from microbes. Grazing intensification can significantly influence N_2O emissions from pasture systems by stimulating the decoupling process, returning more nutrients to the soil. A study conducted in an alpine meadow on the eastern Qinghai–Tibet Plateau found that N_2O emissions varied with grazing intensity, with annual mean emissions recorded at 1.17 ± 0.50 kg N_2O ha^{-1} yr^{-1} for non-grazing conditions and 1.94 ± 0.23 kg N_2O ha^{-1} yr^{-1} for grazing lands (Evans et al., 2019). This indicates that grazing can increase N_2O emissions by approximately 65% compared to non-grazing scenarios. In another study in South Africa, it was reported that N_2O emissions from irrigated dairy-pasture systems ranged from 2.45 to 15.5 kg N_2O-N ha^{-1} yr^{-1}, with the highest daily fluxes occurring during spring and summer, reaching up to 1.52 kg N_2O ha^{-1} day^{-1} (Smit et al., 2020). This suggests that the management of grazing intensity and fertilizer application can lead to substantial variations in N_2O emissions, with higher emissions associated with increased nitrogen inputs and grazing pressure.

C is an energy source and building block for plant tissues. It forms an integral part of the structural component of plant carbohydrates, cellulose, and hemicellulose as well as sugars and plant protein. The outflow of C in this pool happens when plants are either harvested as crop, ingested by animals during grazing, or forms part of the litter, which will eventually be decomposed and sequestrated in soil.

The aboveground inflow of N originates from available N in the soil, which is dependent on microbial activity, water availability and plant roots, among other factors. Ideally, plant uptake of N should be optimised with minimal losses to the environment to produce nutrients in the form of amino acids and proteins in the plant and, in turn, affect the nutritional value of crops. Many factors can impact the efficiency of the photosynthesis process and the uptake of nutrients from soil. The efficiency of photosynthesis and nutrient uptake is influenced by several key factors, each contributing quantitatively to plant growth and biomass production. Light intensity is a primary driver; for instance, increasing light intensity can enhance the rate of photosynthesis by up to 200% until a saturation point is reached, beyond which the rate levels off (Li et al., 2023). Additionally, nutrient availability, particularly nitrogen, directly affects plant biomass, as nitrogen is essential for synthesizing chlorophyll and amino acids. Plants deficient in nitrogen can exhibit reduced growth rates, with biomass production decreasing by 30–50% compared to adequately fertilized plants (Evans et al., 2019).

Utilising the strong connections between these factors will have a marked effect on plant growth and consequently biomass production that can be achieved. Soussana and Lemaire (2014) describe the strong connection between the N and C cycles involved in pasture systems through soil microbial heterotrophy and the elemental balance of plant autotrophy. The C:N of organic matter and soil can be enhanced through plant species diversity, regulation of N-fixation, and plant function. Other important factors that will impact photosynthesis are water availability, the concentration of atmospheric CO_2 and temperature. In a study done by Chen et al. (2022), where plants were analysed on 68 sites around the world, the rate of photosynthesis has risen since 2000. The higher atmospheric CO_2 concentrations contributed to an increase in the surface area of leaves, likely due to increased water use efficiency. The increase in photosynthesis with elevated CO_2 levels, can imply even faster growth and higher carbon sequestration. Wilson et al. (2018) revealed that grazing accelerates the photosynthesis process, can avoid the deterioration of grass pasture, and lowers the risk of emissions through fire. External returns onto pasture can support nutrient cycling and increase primary production at a moderate grazing rate, and animal tramping on pasture can reduce leaf area and photosynthetic capacity, which also have an impact on the cycling of nutrients in the system (Soussana and Lemaire, 2014).

Several authors have studied the effect of different levels of N fertiliser application and suggested that declining soil fertility in Kikuyu-ryegrass (*Cenchrus clandestinus*—Lolium spp.) pastures in South Africa has negative environmental costs. Swanepoel et al. (2015) found that minimum-tillage kikuyu-ryegrass pastures had elevated levels of extractable phosphorus and zinc, which can have detrimental effects on soil fertility. Miles (1997) found that kikuyu pastures require N and phosphorus fertilisers to maintain productivity while Phohlo et al. (2022) found that high N fertiliser rates did not necessarily translate to higher herbage yield of pastures, and that N use efficiency improved with reduced N application rates. Swanepoel et al. (2014) developed a soil quality index for kikuyu-ryegrass pastures in the southern Cape of South Africa, which can be used to monitor soil fertility and sustainability. Overall, these papers suggest that declining soil fertility in kikuyu-ryegrass pastures can have negative environmental impacts and that proper fertilisation and soil management strategies are necessary to maintain productivity and sustainability.

In research from Beukes et al. (2020) increased animal and pasture production was achieved at the cost of efficiencies from N in the soil and higher N being lost as emissions. These authors suggested that neither maximum N output per animal nor striving for too low levels of N fertiliser input should be the goal since both these scenarios have either a negative impact on the environment or production output; hence, striving for relatively low N losses while achieving relative high N output. This is consistent with the research from Soussana and Lemaire (2014) who learned that excessive N and P fertiliser applications had an increased effect on C flows from the atmosphere to the soil. However, this process is altered with increased animal intake which reduces C residence time in the system, resulting in more N lost to the environment. Another outflow of N in this system is from urine patches where nitrate (NO_3^-) leaches to water bodies and N_2O volatilises into the atmosphere (Monaghan and De Klein, 2014).

One strategy to increase pasture growth per hectare is through N fertiliser application and irrigation. The higher roughage availability can increase milk production per hectare through an increased stocking rate. However, when production per hectare is too high, it can negatively impact the environment and increase GHG emissions. It is, therefore, critical to increase pasture production through optimal N-use efficiency which can support optimal stocking density and highest milk production (Galloway et al., 2018). This correlates with the study from Soussana and Lemaire (2014) where excessive active N forms resulted in intricate responses, such as reduction of C sequestration. The fertiliser application will be further discussed in the belowground section.

6 C and N flow in belowground pool (soil)

Various research studies suggest that the combined application of manure and inorganic fertilisers can increase the organic carbon sequestration rate and stability in soil and minimise soil organic losses (Rayne and Aula, 2020; Gao et al., 2021; Mustafa et al., 2021; Huang et al., 2022). In a field study conducted by Wang et al. (2022), they found that the application of manure fertiliser yielded higher soil organic C concentrations in differently sized soil aggregates compared to inorganic fertiliser alone. The rates of soil organic C increase were positively correlated with the proportion of organic to inorganic fertiliser applied. Zhang et al. (2022) found that long-term manure application enhanced the stability of aggregates and aggregate-associated carbon by regulating soil physicochemical characteristics. A meta-analysis by Rome Gross and Glaser (2021) found that manure application on agricultural soils increased soil organic C stocks by 35.4% on average, corresponding to 10.7 t ha^{-1}. When manure applications were combined with additional mineral fertiliser, the soil organic C increases were even higher compared to manure alone.

Many pasture management practices favour organic C sequestration in pasture soils, such as grazing frequency and intensity (leading to root turnover), nutrient cycling through animal excreta, no or minimum soil disturbance, increase in herbage biomass productivity, forage type, fertilisation, and grazing frequency and intensity. Moderate or low grazing intensity led to a higher potential for soil organic C accumulation in an integrated crop-livestock system under no-tillage (Cecagno et al., 2018).

Meyer et al. (2015) investigated pastures with low and high-carbon soils and found that soils with high carbon tend to have increased herbage productivity, increased N mineralisation, and higher N availability, all factors that improve on-farm benefits. Another study observed the effects of grazing pastures which can improve both soil organic C and soil organic N because of the significantly increased biomass from root litter deposition that increases belowground soil organic C which in turn contributed to increased root system production and turnover (Wilson et al., 2018). Another benefit from soil organic C is that it can act as a buffer to stored nutrients when availability is high and provide nutrients during low availability of nutrients (Fontaine et al., 2011).

Nutrient flows enter soil through urine and manure deposits from animal manure and plant litter. The organic nutrients from animal excrements accelerate nutrient flow and after mineralisation become available to plants. This soil organic matter serves as a pool for nutrients needed by plants, it can enhance soil aggregation and nutrient exchange, promote structure, and physical and biological health in soil, and consequently accelerate plant growth (Soumare et al., 2020). Increasing grazing intensity can therefore increase the return of C and N to soil.

The possibility of soil carbon to provide climate change mitigation and adaption benefits is very often described in the literature because of its abilities such as increasing N supply and plant available water holding capacity as well as greater pasture production yield (Meyer et al., 2015). It is estimated that the potential reduction of C in the atmosphere can be in the range of 0.79 and 1.54 Gt C per year with soil C sequestration (Fuss et al., 2018).

The processes of nitrification and denitrification are dictated by the substrate and soil organic matter. Inorganic N from fertiliser application and microbial mineralisation, manure and organic matter transform N through the nitrification and denitrification processes. These processes are influenced by different factors such as soil temperature, moisture, oxygen availability, and the amount and types of microbes present. For example, denitrification occurs during high moisture conditions in soil or when oxygen is absent and will transfer nitrate and some ammonia into atmospheric N. Studies in this area presented by Berglund et al. (2009) and Bouwman et al. (2002) show draughts and drainage are related to reduction in N_2O emissions while a high precipitation, freeze and thaw periods, clay and organic soils, high pH, N application, soil compaction and tillage lead to increased N_2O emissions. The study conducted by Smit et al. (2020) aimed to quantify direct N_2O emissions from a pasture system under irrigation in South Africa. The study demonstrated that grazing under irrigation affects N_2O emissions substantially, and the relationship between N balance and annual N_2O emissions was exponential, indicating that excessive fertilisation of N will add directly to N_2O emissions. The authors suggest that the results of this study can be used to improve N_2O emission inventories and to develop mitigation strategies for agricultural systems in South Africa. These complex biological processes that produce N_2O are generally not considered when estimating N_2O in dairy carbon footprint studies (Flysjö, 2012). In general, N lost from the soil mainly happens through volatilisation of ammonia and N leaching (mainly as NO_3). Leaching, ammonia volatilisation, and surface run-off lead to non-bacterial losses of N.

Several studies provide insights into the role of microbial necromass in soil processes and carbon turnover. Kästner et al. (2021) emphasise the importance of microbial necromass as a resource in soil organic matter, suggesting that microorganisms can mobilise building blocks from necromass to optimise carbon and energy use. Potthoff et al. (2006) investigated the impact of restoration practices on microbial community composition and found that the presence or absence of plants significantly influences microbial communities. The study highlights the importance of considering the role of plants in shaping soil microbial communities and the potential for restoration practices to promote beneficial microbial communities. Another study found that microbial necromass recycling efficiency is not sensitive to historical land use intensity, but does negatively correlate with historical precipitation (Buckeridge et al., 2020). These authors found recycling efficiency increased with microbial growth rate on necromass and was highest in soils with low historical precipitation. Naylor et al. (2022) emphasise the importance of considering deeper soils in soil microbiome studies, as microbial community composition and functional profiles vary with depth. Soil edaphic properties such as chemical composition and physical structure change from surface layers to deeper ones, and the soil microbiome similarly exhibits substantial variability with depth, hence the author suggests the soil C modelling approaches should consider the effect of microorganisms in sub-soils to increase accuracy in predictions of C fluxes. In contrast, Von Lützow et al. (2002) found the soil organic C in topsoil is the central characteristic that provides the structure and biochemical conditions needed for sustainable and productive agriculture, while Liu et al. (2021) emphasise the role of cultivation, crop rotation, residue, tillage management, fertilisation and monoculture in affecting soil organic C and its transformation. Overall, these papers emphasise the significance of microbial necromass in soil processes and highlight the need for further research to understand its role in carbon stabilisation.

A recent meta-analysis estimates that mycorrhizal fungi receive as much as 13.12 Gt of carbon dioxide equivalents (CO_2e) annually, which is roughly equivalent to 36% of yearly global fossil fuel emissions (Hawkins et al., 2023). This finding highlights the significant role of mycorrhizal mycelium as a global carbon pool. The study suggests that mycorrhizal fungi play a crucial role in transporting carbon into soil ecosystems on a global scale, with 70–90% of land plants forming symbiotic relationships with these fungi. While the mechanisms by which mycorrhizal fungi affect soil carbon pools are still being explored, they have a significant impact on global carbon fluxes. This highlights the need for further research to fully understand the role of mycorrhizal mycelium in the global carbon cycle and to identify approaches to increase our understanding of global carbon fluxes via mycorrhizal mycelium.

There are many advantages to relying on biological N fixation as opposed to mineral N fertilisers, since it can reduce input costs, decrease emissions, and enhance the digestibility and content of herbage (Ladha et al., 2022). Another advantage of biological N fixation is that N is already attached to the corresponding C thus preventing build-up from reactive N in soil which can cause N leaching (Soumare et al., 2020). Furthermore, rhizobium bacteria have a symbiotic interaction with legumes which increases plant access to N legumes and allows the rhizobia to enter their roots and form nodules, where the bacteria can convert atmospheric N into a form that the plant can use (Wang et al., 2018).

Decomposing microbes in the soil are primarily responsible for biological degradation of biological matter. These microbes can largely control the C:N in soil organic matter since they have a relatively fixed C:N ratio (Liang et al., 2019). Large deposits from plant material that consists of a high C:N ratio returning to the soil release a large amount of CO_2, which further generates a rapid N mineralisation-immobilisation turnover from microbial activity. The net mineralisation, which is N released in mineral forms (ammonium and nitrate) happens relatively fast in grasslands (Maire et al., 2009) and N_2O emissions occur mostly around urine patches and just after N fertiliser application.

Another important consideration is the effect of soil management. Reducing soil disturbance through avoiding tillage is the temporary status of soil C sequestration which can rapidly be lost through processes such as soil disturbance, erosion, fire and drought (Haddaway et al., 2016). This practice can also save fuel and allow farmers to use lighter machinery. The different management strategies (conservation tillage, minimum tillage and no-tillage) is a much debated subject. Minimum tillage and re-sowing pastures have shown potential for C storage, since it appears that soil organic C increases proportional to lifespan, especially with perennial cover (Francaviglia et al., 2023).

From the above, it is therefore imperative to implement optimal fertiliser management strategies, which consider N mineralisation, address the needs of plants, without accumulation of excess nutrients and consider the current soil fertility status. Excess fertiliser application does not contribute to additional production. Improving soil health and producing more from less input can improve soil health, increase production, and prevent accumulation and its negative impacts on the environment (Phohlo et al., 2022; Francaviglia et al., 2023).

In addition to more research to better understand the nutrient flux in soil, more tools need to be developed to understand the interconnectedness of this system. For example, Swanepoel et al. (2014) developed a soil quality index, which includes physical, chemical and biological indicators for pasture systems in South Africa using principal component analyses from minimal input data to help farmers manage their pasture goals and adapt to strategies that could enhance conservation agriculture. Although this specific model was developed for a kikuyu-ryegrass pasture, the indicators within this model can provide a valuable basis for soil management and restoring soils from pastures.

Critical to economic stability related to the environmental impact and soil quality, the study by Musto et al. (2023) offers valuable insights into the effects of regenerative versus conservation agriculture practices. This research is highly relevant to pasture dairy farming in South Africa, where the industry faces challenges related to environmental sustainability and economic viability. Implementing regenerative agriculture practices can help address soil degradation and nutrient management, which are critical issues for South African dairy farmers. Musto et al. highlight that these practices improve soil health by increasing organic carbon levels, leading to enhanced pasture quality and potentially higher milk yields. Given the rising costs and declining profits currently experienced in the dairy sector, the economic benefits of regenerative practices—such as reduced dependency on chemical inputs and improved resource efficiency—are particularly significant.

7 Pasture management and species composition

As implicated above, pasture-based systems has the potential to significantly decrease GHG emissions by facilitating soil carbon sequestration (Salvador et al., 2017). The effective management of pastures to yield high N crops can contribute to improved soil fertility, carbon sequestration, and reduced greenhouse gas emissions, particularly methane. Research has shown that forages with high nutritive value can play a vital role in reducing greenhouse gas emissions, especially enteric CH_4 and nitrous oxide. For instance, Franzluebbers (2020) emphasises the importance of forages with high nutritive value in reducing greenhouse gas emissions, particularly enteric CH_4 and nitrous oxide. De Azevedo et al. (2021) demonstrate that maximising forage intake improves nutrient utilisation efficiency and mitigates methane emissions in lambs. Bolletta (2020) suggests that non-traditional legume forages, such as birdsfoot trefoil (*Lotus corniculatus*), can enhance pasture productivity, increase soil organic C, and potentially reduce enteric methane emissions.

The C sequestration potential in grassland systems, and even more so when sown with legume mixtures is higher compared to natural vegetation, because of its deep-rooted system and deep soil has a higher C storage potential than topsoil (Neal et al., 2013). However, to support production on grassland pastures, it is important to have sufficient available soil nutrients such as N, P, K and proper liming (Soussana and Lemaire, 2014). Apart from the impact from forage type, effective pasture use involves achieving optimal stocking rates, milk production with minimal concentrate feed, and efficient use of pasture. Rotational pasture management is beneficial in achieving these goals (Beukes et al., 2020; Clark et al., 2016). Optimal grazing management contributes to an increase in soil carbon, lower N levels, and increased N use efficiencies. This is due to an increase in carbon cycling, which supports nutrient availability in the soil (Paustian et al., 2016; Galloway et al., 2018).

The introduction of a diverse range of pasture species can bring about significant economic benefits when compared to traditional single or binary grass pastures. This approach is gaining popularity in current pasture systems, especially considering the growing concern about the leaching of N into natural water sources. Planting diverse pastures can alleviate this concern, as it contributes to a reduction of N lost due to leaching. For instance, if all pastures are sown with diverse species, a predicted reduction of 40% in N leaching can be achieved (Beukes et al., 2020).

Incorporating diverse pastures in farming is therefore an effective and affordable method to reduce N leaching. This is achieved through a reduction in the N concentration found in urine patches, which ultimately leads to lower N leaching from pastures (Romera et al., 2017). Studies on the effects of plants such as chicory (*Cichorium intybus*) and plantain (*Plantago lanceolata*) have demonstrated their ability to act as diuretics, thereby reducing the N content in urine patches (Pembleton et al., 2015). By increasing urine volume, these plants effectively lower the concentration of N in urine and promote a healthier pasture ecosystem. According to a study by Totty et al. (2013), reducing N excretion can be achieved through a balanced ratio of water-soluble carbohydrates and protein, improved N utilisation in the rumen, and the presence of plant secondary compounds that increase water intake and urination volume. These approaches have demonstrated success in reducing N concentrations.

A study by Rodríguez et al. (2022) also highlights the importance of the keystone role of the N_2 fixation rate of legumes on C stocks in natural grasslands and provides a strong argument for species diversity conservation efforts under climate change conditions. Teixeira et al. (2019) and Kumar et al. (2020) noted that legumes can fix N and store 30% more soil organic C compared to other species. These grass-legume pastures with high diversity also increased pasture productivity by promoting higher yields. This was attributed to increased microbial biomass, diversity and activity, leading to higher soil carbon stocks. For the best results in diverse grass-legume pastures, it is advised that they comprise approximately 30–50% legumes. These studies provide valuable insights into the benefits of diverse pastures and the role of legumes in nutrient cycling and carbon sequestration.

Incorporating cover crops into dairy farming practices is typically associated with silage production, but it can also provide the necessary crop diversity for conservation agriculture, particularly when including N-fixing legumes (Franke et al., 2018). While challenging to implement successfully due to climatic and soil conditions, cover crops can enhance soil quality, improve productivity, and increase sustainability when integrated with livestock for grazing or haymaking purposes (Bell et al., 2018). This approach can also mitigate feed gaps and promote carbon sequestration in the soil, adding diversification benefits to the overall cropping system, improving productivity, and enhancing sustainability (Smit H. P. et al., 2021).

8 A research agenda for enhancing environmental sustainability in the south African dairy industry

The dairy sector faces significant challenges related to its environmental footprint, encompassing issues such as greenhouse gas (GHG) emissions, N release into water and the atmosphere, and water pollution. Currently, there is a lack of comprehensive monitoring of the environmental impact of dairy farms, despite its critical implications for production cost and profitability. To address these concerns and promote sustainable practices in the dairy industry, the following research agenda is proposed:

1. Develop comprehensive environmental monitoring strategies
    - Investigate and design effective monitoring protocols for environmental indicators on dairy farms, with a focus on real-time data collection and analysis.
    - Explore innovative technologies and methodologies for tracking GHG emissions, N runoff, and land-use changes to establish a baseline for environmental impact assessment.

2. Integration of research and practical solutions
    - Promote the integration of research findings into practical management strategies for dairy farms.
    - Collaborate with industry stakeholders to bridge the gap between research outcomes and on-farm implementation, with a focus on addressing soil degradation and reduced pasture fertility.

3. Aligning environmental impact with profitability
    - Investigate the economic consequences of sustainable dairy farming practices, including the potential for reducing production costs and increasing profitability.
    - Assess the feasibility of aligning stricter fertiliser guidelines with soil nutrient build-up, enhancing nutrient use efficiency and circulation of nutrients on farms, while maintaining profitability and minimising environmental impact.

4. Communication and market influence
    - Develop and implement strategies to align the dairy industry with evolving consumer demands and address climate footprint perceptions.
    - Investigate the impact of stakeholder and consumer perceptions on market behaviour and the demand for sustainable dairy products.

5. On-site environmental impact assessment
    - Create tools for dairy farmers to monitor on-site environmental impacts and express these in monetary terms.
    - Develop protocols for precautionary and mitigating adaptive measures to address environmental issues promptly.

6. Carbon capture and storage assessment
    - Explore methodologies to estimate the carbon capturing and storage capacity within on-farm dairy production systems.
    - Analyse critical nutrient flows within dairy systems to determine if farms are carbon emission sources or sinks.

7. Individualised carbon footprint assessment
    - Investigate the variation in net GHG emissions among individual cows, herds and farms, considering factors such as metabolisable energy requirements, physiological status and milk production.
    - Develop tools and models to determine the net GHG emissions or sinks at the individual and farm levels based on specific parameters and conditions.

8. Complex system modelling
    - Explore the complexity of estimating carbon sequestration and the role of cows as biogenic sources of carbon.
    - Identify and integrate variables that impact carbon emissions and sequestration into the proposed tool, creating a comprehensive and adaptable system for environmental assessment in the dairy industry.

In conclusion, this research agenda aims to provide dairy farmers and the industry with the necessary knowledge and tools to adopt environmentally sustainable practices, improve competitiveness, and reduce the risk of environmental failure. It also seeks to enhance transparency and consumer trust by aligning environmental impact with profitability, ultimately driving the dairy industry toward a more sustainable future.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RR: Conceptualization, Investigation, Writing – original draft. JB: Conceptualization, Funding acquisition, Supervision, Validation, Visualization, Writing – review & editing. HM: Funding acquisition, Project administration, Writing – review & editing. PS: Conceptualization, Supervision, Validation, Visualization, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. The research team gratefully acknowledge research funding received from Milk SA, project number 0331-2022, as implemented by ASSET Research.

Acknowledgments

The administrative support of L van der Elst is also acknowledged.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Adler, A. A., Doole, G. J., Romera, A. J., and Beukes, P. C. (2013). Cost-effective mitigation of greenhouse gas emissions from different dairy systems in the Waikato region of New Zealand. *J. Environ. Manag.* 131, 33–43. doi: 10.1016/j.jenvman.2013.09.038

Baral, K. R., Jégo, G., Amon, B., Bol, R., Chantigny, M. H., Olesen, J. E., et al. (2018). Greenhouse gas emissions during storage of manure and digestates: key role of methane for prediction and mitigation. *Agric. Syst.* 166, 26–35. doi: 10.1016/j.agsy.2018.07.009

Basarab, J. A., Beauchemin, K. A., Baron, V. S., Ominski, K., Guan, L., Miller, S., et al. (2013). Reducing GHG emissions through genetic improvement for feed efficiency: effects on economically important traits and enteric methane production. *Animal* 7, 303–315. doi: 10.1017/S1751731113000888

Beauchemin, K. A., Kreuzer, M., O'Mara, F., and McAllister, T. A. (2008). Nutritional management for enteric methane abatement: a review. *Aust. J. Exp. Agric.* 48, 21–27. doi: 10.1071/EA07199

Bell, L. W., Moore, A. D., and Thomas, D. T. (2018). Integrating diverse forage sources reduces feed gaps on mixed crop-livestock farms. *Animal* 12, 1967–1980. doi: 10.1017/S1751731117003196

Berglund, M., Cederberg, C., Clason, C., Henriksson, M., and Törner, L. (2009). Agriculture's contribution to climate change – bases for calculating greenhouse gas emissions at farm level and baseline analysis of test farms. Part of the JOKER project; in Swedish. Halmstad, Sweden: Hushållningssällskapet Halland.

Beukes, P. C., Gregorini, P., Cameron, K., and Attwood, G. T. (2020). Farm-scale carbon and nitrogen fluxes in pastoral dairy production systems using different nitrogen fertilizer regimes. *Nutr. Cycl. Agroecosyst.* 117, 1–12. doi: 10.1007/s10705-020-10052-2

Blignaut, J. N., Meissner, H., Smith, H., and Du Toit, L. (2022). An integrative bio-physical approach to determine the greenhouse gas emissions and carbon sinks of a cow and her offspring in a beef cattle operation: a system dynamics approach. *Agric. Syst.* 195:103286. doi: 10.1016/j.agsy.2021.103286

Bolletta, A. I. (2020). Enhancing the production and sustainability of pasture-fed beef using non-traditional legume forages. Utah: Utah State University.

Bouwman, A. F., Boumans, L. J. M., and Batjes, N. H. (2002). Emissions of N2O and NO from fertilized fields: summary of available measurement data. *Glob. Biogeochem. Cycles* 16:1811. doi: 10.1029/2001gb001811

Buckeridge, K. M., Mason, K. E., McNamara, N. P., Ostle, N., Puissant, J., Goodall, T., et al. (2020). Environmental and microbial controls on microbial necromass recycling, an important precursor for soil carbon stabilization. *Commun. Earth Environ.* 1:36. doi: 10.1038/s43247-020-00031-4

Cecagno, D., Gomes, M. V., Costa, S., Martins, A., Denardin, L., Bayer, C., et al. (2018). Soil organic carbon in an integrated crop-livestock system under different grazing intensities. Revista Brasileira de Ciências Agrárias - Brazilian. *J. Agric. Sci.* 13, 1–7. doi: 10.5039/agraria.v13i3a5553

Chang, J., Peng, S., Yin, Y., Ciais, P., Havlik, P., and Herrero, M. (2021). The key role of production efficiency changes in livestock methane emission mitigation. *AGU Adv.* 2:391. doi: 10.1029/2021av000391

Charmley, E., Williams, S. R. O., Moate, P., Hegarty, R., Herd, R., Oddy, H., et al. (2016). A universal equation to predict methane production of forage-fed cattle in Australia. *Anim. Prod. Sci.* 56:169. doi: 10.1071/AN15365

Chen, Z., Liu, F., Cai, G., Peng, X., and Wang, X. (2022). Responses of soil carbon pools and carbon management index to nitrogen substitution treatments in a sweet maize farmland in South China. *Plants (Basel)* 11:2194. doi: 10.3390/plants11172194

Clark, C. E. F., Farina, S. R., Garcia, S. C., Islam, M. R., Kerrisk, K. L., and 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, 153–159. doi: 10.1111/gfs.12171

Cottle, D., Eckard, R., Bray, S., and Sullivan, M. (2016). An evaluation of carbon offset supplementation options for beef production systems on coastal speargrass in Central Queensland, Australia. *Anim. Prod. Sci.* 56:385. doi: 10.1071/AN15446

Dalby, F. R., Hafner, S. D., Petersen, S. O., VanderZaag, A. C., Habtewold, J., Dunfield, K., et al. (2021). Understanding methane emission from stored animal manure: a review to guide model development. *J. Environ. Qual.* 50, 817–835. doi: 10.1002/jeq2.20252

De Azevedo, E. B., Savian, J. V., Do Amaral, G. A., De David, D., Gere, J., Kohmann, M., et al. (2021). Feed intake, methane yield, and efficiency of utilization of energy and nitrogen by sheep fed tropical grasses. *Trop. Anim. Health Prod.* 53:452. doi: 10.1007/s11250-021-02928-4

Evans, K. S., Mamo, M., Wingeyer, A., Schacht, W. H., Eskridge, K. M., Bradshaw, J., et al. (2019). Soil Fauna accelerate dung pat decomposition and nutrient cycling into grassland soil. *Rangeland Ecol. Man.* 72, 667–677. doi: 10.1016/j.rama.2019.01.008

FAO (2006). Livestock's long shadow – Environmental issues and options. Rome: Food and Agriculture Organization of the United Nations.

Faverdin, P., Delagarde, R., Delaby, L., and Meschy, F. (2007). Réactualisation des équations du livre rouge: alimentation des vaches laitières. Versailles: Quae, 23–55.

Feng, X., and Kebreab, E. (2020). Net reductions in greenhouse gas emissions from feed additive use in California dairy cattle. *PLoS One* 15:e0234289. doi: 10.1371/journal.pone.0234289

Flysjö, A. (2012). Greenhouse gas emissions in milk and dairy product chains, PhD Thesis. Science and Technology, Aarhus University, Denmark.

Fontaine, S., Henault, C., Aamor, A., Bdioui, N., Bloor, J., Maire, V., et al. (2011). Fungi mediate long term sequestration of carbon and nitrogen in soil through their priming effect. *Soil Biol. Biochem.* 43, 86–96. doi: 10.1016/j.soilbio.2010.09.017

Francaviglia, R., Almagro, M., and Vicente-Vicente, J. L. (2023). Conservation agriculture and soil organic carbon: principles, processes, practices and policy options. *Soil Syst.* 7:17. doi: 10.3390/soilsystems7010017

Franke, A. C., Van den Brand, G. J., Vanlauwe, B., and Giller, K. E. (2018). Sustainable intensification through rotations with grain legumes in sub-Saharan Africa: a review. *Agric. Ecosyst. Environ.* 261, 172–185. doi: 10.1016/j.agee.2017.09.029

Franzluebbers, A. J. (2020). "Cattle grazing effects on the environment: greenhouse gas emissions and carbon footprint" in Management strategies for sustainable cattle production in southern pastures. eds. M. Rouquette and G. E. Aiken (Cambridge, Mass: Academic Press).

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., et al. (2018). Negative emissions - part 2: costs, potentials and side effects. *Env. Res. Lett.* 13:6. doi: 10.1088/1748-9326/aabf9f

Galloway, C., Conradie, B., Prozesky, H., and Esler, K. (2018). Are private and social goals aligned in pasture-based dairy production? *J. Clean. Prod.* 175, 402–408. doi: 10.1016/j.jclepro.2017.12.036

Gao, Y., Lu, Y., Liao, Y., and Nie, J. (2021). Higher soil organic carbon accumulation in the subsoil layer by 37 years combined application of inorganic fertilizers with manure than with rice straw in a double-rice paddy soil. *Arch. Agron. Soil Sci.* 68, 1075–1088. doi: 10.1080/03650340.2020.1869216

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., et al. (2013). Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO),

Grossi, G., Goglio, P., Vitali, A., and Williams, A. G. (2019). Livestock and climate change: impact of livestock on climate and mitigation strategies. *Anim. Front.* 9, 69–76. doi: 10.1093/af/vfy034

Hackmann, T. J., Ngugi, D. K., Firkins, J. L., and Tao, J. (2017). Genomes of rumen bacteria encode atypical pathways for fermenting hexoses to short-chain fatty acids. *Environ. Microbiol.* 19, 4670–4683. doi: 10.1111/1462-2920.13929

Haddaway, N. R., Hedlund, K., Jackson, L. E., Kätterer, T., Lugato, E., Thomsen, I. K., et al. (2016). How does tillage intensity affect soil organic carbon? A systematic review protocol. *Environ. Evid.* 5:1. doi: 10.1186/s13750-016-0052-0

Harrison, M. T., Cullen, B. R., Mayberry, D. E., Cowie, A., Bilotto, F., Badgery, W., et al. (2021). Carbon myopia: the urgent need for integrated social, economic and environmental action in the livestock sector. *Glob. Chang. Biol.* 27, 5726–5761. doi: 10.1111/gcb.15816

Hawkins, H. J., Cargill, R. I. M., Van Nuland, M. E., Hagen, S., Field, K., Sheldrake, M., et al. (2023). Mycorrhizal mycelium as a global carbon pool. *Curr. Biol.* 33, R560–R573. doi: 10.1016/j.cub.2023.02.027

Hristov, A. N., Oh, J., Firkins, J. L., Dijkstra, J., Kebreab, E., Waghorn, G., et al. (2013). Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. *J. Anim. Sci.* 91, 5045–5069. doi: 10.2527/jas.2013-6583

Huang, X., Jia, Z., Jiao, X., Wang, J., and Huang, X. (2022). Long-term manure applications to increase carbon sequestration and macroaggregate-stabilized carbon. *Soil Biol. Biochem.* 174:108827. doi: 10.1016/j.soilbio.2022.108827

IPCC (2019). Chapter 10 emissions from livestock and manure management. Cambridge: Cambridge University Press.

Kästner, M., Miltner, A., Thiele-Bruhn, S., and Liang, C. (2021). Microbial Necromass in soils—linking microbes to soil processes and carbon turnover. *Front. Environ. Sci.* 9:756378. doi: 10.3389/fenvs.2021.756378

Knapp, J. R., Laur, G. L., Vadas, P. A., Weiss, W. P., and Tricarico, J. M. (2014). Invited review: enteric methane in dairy cattle production: quantifying the opportunities and impact of reducing emissions. *J. Dairy Sci.* 97, 3231–3261. doi: 10.3168/jds.2013-7234

Kumar, R., Yadav, M. R., Arif, M., Mahala, D., Kumar, D., Ghasal, P., et al. (2020). Multiple agroecosystem services of forage legumes towards agriculture sustainability: an overview. *Indian J. Agric. Sci.* 90, 1367–1377. doi: 10.56093/ijas.v90i8.105882

Ladha, J. K., Peoples, M. B., Reddy, P. M., Biswas, J., Bennett, A., Jat, M., et al. (2022). Biological nitrogen fixation and prospects for ecological intensification in cereal-based cropping systems. *Field Crop Res.* 283:108541. doi: 10.1016/j.fcr.2022.108541

Lean, I. J., and Moate, P. J. (2021). Cattle, climate and complexity: food security, quality and sustainability of the Australian cattle industries. *Aust. Vet. J.* 99, 293–308. doi: 10.1111/avj.13072

Li, Y. T., Gao, H. Y., and Zhang, Z. S. (2023). Effects of environmental and non-environmental factors on dynamic photosynthetic carbon assimilation in leaves under changing light. *Plants (Basel, Switzerland)* 12:2015. doi: 10.3390/plants12102015

Liang, C., Amelung, W., Lehmann, J., and Kästner, M. (2019). Quantitative assessment of microbial necromass contribution to soil organic matter. *Glob. Chang. Biol.* 25, 3578–3590. doi: 10.1111/gcb.14781

Liu, S., Proudman, J., and Mitloehner, F. (2021). Rethinking methane from animal agriculture. *CABI Agric. Biosci.* 2:22. doi: 10.1186/s43170-021-00041-y

Lynch, J., Cain, M., Pierrehumbert, R., and Allen, M. (2020). Demonstrating GWP: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Env. Res. Lett.* 15:044023. doi: 10.1088/1748-9326/ab6d7e

MacLaren, C., Storkey, J., Strauss, J., Swanepoel, P., and Dehnen-Schmutz, K. (2019). Livestock in diverse cropping systems improve weed management and sustain yields whilst reducing inputs. *J. Appl. Ecol.* 56, 144–156. doi: 10.1111/1365-2664.13239

Maire, V., Gross, N., Da Silveira Pontes, L., Picon-Cochard, C., and Soussana, J.-F. (2009). Trade-off between root nitrogen acquisition and shoot nitrogen utilization across 13 co-occurring pasture grass species. *Funct. Ecol.* 23, 668–679. doi: 10.1111/j.1365-2435.2009.01557.x

Meyer, R., Cullen, B. R., Johnson, I. R., and Eckard, R. J. (2015). Process modelling to assess the sequestration and productivity benefits of soil carbon for pasture. *Agric. Ecosyst. Environ.* 213, 272–280. doi: 10.1016/j.agee.2015.07.024

Miles, N. (1997). Responses of productive and unproductive kikuyu pastures to top-dressed nitrogen and phosphorus fertiliser. *Afr. J. Range Forage Sci.* 14, 1–6. doi: 10.1080/10220119.1997.9647911

Milk Producers' Organisation (MPO) (2023). Challenges in the south African dairy industry. Retrieved from MPO.

Milk SA (2024). Lacto data, quarterly review of the performance of the dairy industry. Retrieved from Milk SA.

Monaghan, R. M., and De Klein, C. A. M. (2014). Integration of measures to mitigate reactive nitrogen losses to the environment from grazed pastoral dairy systems. *J. Agric. Sci.* 152, 45–56. doi: 10.1017/S0021859613000956

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., and Cleemput, O. (1998). Closing the global atmospheric N2O budget: nitrous oxide emissions through the agricultural nitrogen cycle; OECD/IPCC/IEA phase II development of IPCC guidelines for National Greenhouse gas Inventories. *Nut. Cyc. Agroecosys.* 52, 225–248. doi: 10.1023/A:1009740530221

Mustafa, A., Abrar, M. M., Atizaz, S., Naveed, M., Kamran, M., and Saeed, Q. (2021). Long-term fertilization alters chemical composition and stability of aggregate-associated organic carbon in a Chinese red soil: evidence from aggregate fractionation, C mineralization, and 13C NMR analyses. *J. Soils Sediments* 21, 2483–2496. doi: 10.1007/s11368-021-02944-9

Musto, G. A., Swanepoel, P. A., and Strauss, J. A. (2023). Regenerative agriculture vs. conservation agriculture: potential effects on soil quality, crop productivity, and whole-farm economics in Mediterranean-climate regions. *J. Agric. Sci.* 161, 328–338. doi: 10.1017/S0021859623000242

Naylor, D., McClure, R., and Jansson, J. (2022). Trends in microbial community composition and function by soil depth. *Microorganisms (Basel)* 10:540. doi: 10.3390/microorganisms10030540

Neal, J. S., Eldridge, S. M., Fulkerson, W. J., Lawrie, R., and Barchia, I. M. (2013). Differences in soil carbon sequestration and soil nitrogen among forages used by the dairy industry. *Soil Biol. Biochem.* 57, 542–548. doi: 10.1016/j.soilbio.2012.09.019

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., and Smith, P. (2016). Climate-smart soils. *Nature* 532, 49–57. doi: 10.1038/nature17174

Pembleton, K. G., Tozer, K. N., Edwards, G. R., Jacobs, J. L., and Turner, L. R. (2015). Simple versus diverse pastures: opportunities and challenges in dairy systems. *Anim. Prod. Sci.* 55, 893–901. doi: 10.1071/AN14816

Phohlo, M. P., Swanepoel, P. A., and Hinck, S. (2022). Excessive nitrogen fertilization is a limitation to herbage yield and nitrogen use efficiency of dairy pastures in South Africa. *Sustainability (Basel, Switzerland)* 14:4322. doi: 10.3390/su14074322

Potthoff, M., Steenwerth, K. L., Jackson, L. E., Drenovsky, R. E., Scow, K. M., and Joergensen, R. G. (2006). Soil microbial community composition as affected by restoration practices in California grassland. *Soil Biol. Biochem.* 38, 1851–1860. doi: 10.1016/j.soilbio.2005.12.009

Rayne, N., and Aula, L. (2020). Livestock manure and the impacts on soil health: a review. *Soil Syst.* 4:64. doi: 10.3390/soilsystems4040064

Reinecke, R., and Casey, N. H. (2017). A whole farm model for quantifying total greenhouse gas emissions on south African dairy farms. *S. Afr. J. Anim. Sci.* 47:883. doi: 10.4314/sajas.v47i6.16

Rodríguez, A., Canals, R. M., and Sebastià, M.-T. (2022). Positive effects of legumes on soil organic carbon stocks disappear at high legume proportions across natural grasslands in the Pyrenees. *Ecosystems* 25, 960–975. doi: 10.1007/s10021-021-00695-9

Rome Gross, A., and Glaser, B. (2021). Meta-analysis on how manure application changes soil organic carbon storage. *Sci. Rep.* 11:5516. doi: 10.1038/s41598-021-82739-7

Romera, A. J., Doole, G. J., Beukes, P. C., Masson, N., and Mudge, P. (2017). The role and value of diverse sward mixtures in dairy farm systems of New Zealand: an exploratory assessment. *Agric. Syst.* 152, 18–26. doi: 10.1016/j.agsy.2016.12.004

Salvador, S., Corazzin, M., Romanzin, A., and Bovolenta, S. (2017). Greenhouse gas balance of mountain dairy farms as affected by grassland carbon sequestration. *J. Environ. Manag.* 196, 644–650. doi: 10.1016/j.jenvman.2017.03.052

Smit, E. H., Strauss, J. A., and Swanepoel, P. A. (2021). Utilisation of cover crops: implications for conservation agriculture systems in a mediterranean climate region of South Africa. *Plant Soil* 462, 207–218. doi: 10.1007/s11104-021-04864-6

Smit, H. P. J., Reinsch, T., Swanepoel, P. A., Kluß, C., and Taube, F. (2020). Grazing under irrigation affects N_2O-emissions substantially in South Africa. *Atmosphere (Basel)* 11:925. doi: 10.3390/atmos11090925

Smit, H. P., Reinsch, T., Swanepoel, P. A., Loges, R., Kluß, C., and Taube, F. (2021). Environmental impact of rotationally grazed pastures at different management intensities in South Africa. *Animals* 11:1214. doi: 10.3390/ani11051214

Soumare, A., Diedhiou, A. G., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S., et al. (2020). Exploiting biological nitrogen fixation: a route towards a sustainable agriculture. *Plants (Basel)* 9:1011. doi: 10.3390/plants9081011

Soussana, J. F., and Lemaire, G. (2014). Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. *Agric. Ecosyst. Environ.* 190, 9–17. doi: 10.1016/j.agee.2013.10.012

Swanepoel, P. A., Botha, P. R., Snyman, H. A., and Du Preez, C. C. (2014). Impact of cultivation method on productivity and botanical composition of a kikuyu–ryegrass pasture. *Afr. J. Range Forage Sci.* 31, 215–220. doi: 10.2989/10220119.2014.903999

Swanepoel, P. A., Du Preez, C. C., Botha, P. R., and Snyman, H. A. (2015). A critical view on the soil fertility status of minimum-till kikuyu–ryegrass pastures in South Africa. *Afr. J. Range Forage Sci.* 32, 113–124. doi: 10.2989/10220119.2015.1008043

Teixeira, R. F. M., Barão, L., Morais, T. G., and Domingos, T. (2019). "BalSim": a carbon, nitrogen and greenhouse gas mass balance model for pastures. *Sustainability (Switzerland)* 11:53. doi: 10.3390/su11010053

Totty, V. K., Greenwood, S. L., Bryant, R. H., and Edwards, G. R. (2013). Nitrogen partitioning and milk production of dairy cows grazing simple and diverse pastures. *J. Dairy Sci.* 96, 141–149. doi: 10.3168/jds.2012-5504

Tubb, C., and Seba, T. (2021). Rethinking food and agriculture 2020-2030: the second domestication of plants and animals, the disruption of the cow, and the collapse of industrial livestock farming. *Indus. Biotech.* 17, 57–72. doi: 10.1089/ind.2021.29240.ctu

Uddin, M. E., Tricarico, J. M., and Kebreab, E. (2022). Impact of nitrate and 3-nitrooxypropanol on the carbon footprints of milk from cattle produced in confined-feeding systems across regions in the United States: a life cycle analysis. *J. Dairy Sci.* 105, 5074–5083. doi: 10.3168/jds.2021-20988

UNCTAD (2023). United Nations conference on trade and development. World investment report 2023: investing in sustainable energy for all. United Nations publication. Sales No. E.23.II.D.17. New York and Geneva.

Ungerfeld, E. M. (2020). Metabolic hydrogen flows in rumen fermentation: principles and possibilities of interventions. *Front. Microbiol.* 11:589. doi: 10.3389/fmicb.2020.00589

Van Wyngaard, J. D. V., Meeske, R., and Erasmus, L. J. (2018). Effect of dietary nitrate on enteric methane emissions, production performance and rumen fermentation of dairy cows grazing kikuyu-dominant pasture during summer. *Anim. Feed Sci. Technol.* 244, 76–87. doi: 10.1016/j.anifeedsci.2018.08.005

Von Lützow, M., Leifeld, J., Kainz, M., Kögel-Knabner, I., and Munch, J. C. (2002). Indications for soil organic matter quality in soils under different management. *Geoderma* 105, 243–258. doi: 10.1016/S0016-7061(01)00106-9

Wang, J., Dai, W., Fang, K., Gao, H., Sha, Z., and Cao, L. (2022). Nutrient characterization in soil aggregate fractions with different fertilizer treatments in greenhouse vegetable cultivation. *Agriculture (Basel)* 12:440. doi: 10.3390/agriculture12040440

Wang, Q., Liu, J., and Zhu, Z. (2018). Genetic and molecular mechanisms underlying symbiotic specificity in legume-Rhizobium interactions. *Front. Plant Sci.* 9:313. doi: 10.3389/fpls.2018.00313

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the Anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

Wilson, C. H., Strickland, M. S., Hutchings, J. A., Bianchi, T., and Flory, S. (2018). Grazing enhances belowground carbon allocation, microbial biomass, and soil carbon in a subtropical grassland. *Glob. Chang. Biol.* 24, 2997–3009. doi: 10.1111/gcb.14070

WWF-SA (2021). World wide fund - South Africa, making a business case for sustainable dairy production. Available at: wwfafrica.awsassets.panda.org/downloads/wwf_nedbank_dairy_business_case_report_v2.pdf (Accessed September 18, 2024).

Zhang, C., Zhao, Z., Li, F., and Zhang, J. (2022). Effects of organic and inorganic fertilization on soil organic carbon and enzymatic activities. *Agronomy (Basel)* 12:3125. doi: 10.3390/agronomy12123125