frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 29 January 2026
DOI 10.3389/fsufs.2025.1717931

Check for updates

OPEN ACCESS

EDITED BY
Anas Hamdani,
National Institute for Agricultural Research, Morocco

REVIEWED BY
Deepthi Kolady,
Oklahoma State University, United States
Karun Kaniyamattam,
Texas A&M University, United States

*CORRESPONDENCE
Lutz Merbold
lutz.merbold@gmail.com

RECEIVED 02 October 2025
REVISED 16 December 2025
ACCEPTED 22 December 2025
PUBLISHED 29 January 2026

CITATION
Paunovic S, Jacobi J, Ndung'u P, Michalscheck M and Merbold L (2026) The potential of the Tool for Agroecological Performance Evaluation (TAPE) to estimate greenhouse gas emissions.
Front. Sustain. Food Syst. 9:1717931.
doi: 10.3389/fsufs.2025.1717931

The potential of the Tool for Agroecological Performance Evaluation (TAPE) to estimate greenhouse gas emissions

Stevan Paunovic[1,2], Johanna Jacobi[1], Phyllis Ndung'u[3], Mirja Michalscheck[2,4] and Lutz Merbold[2,4]*

[1]Agroecological Transitions Group, Institute of Agricultural Sciences, Department of Environmental Systems Science, ETH Zurich, Universiätsstrasse, Zurich, Switzerland, [2]Integrative Agroecology Group, Research Division Agroecology and Environment, Agroscope, Zurich, Switzerland, [3]Animal Production and Health Division, Food and Agriculture Organization, Rome, Italy, [4]Mazingira Center, International Livestock Research Institute (ILRI), Nairobi, Kenya

Introduction: The agricultural sector faces increasing pressure to contribute to the Sustainable Development Goals (SDGs) while simultaneously acting as a driver of global climate change. In response, agroecology amongst other approaches is gaining recognition as a holistic framework to transform food systems towards greater sustainability and resilience.
Methods: To facilitate standardized assessment of agroecological performance, the Tool for Agroecology Performance Evaluation (TAPE) was developed by the UN Food and Agriculture Organization (FAO). While a greenhouse gas (GHG) emission score was originally envisioned within the TAPE framework, to date, no standardized implementation exists.
Results: This study presents a first step toward operationalizing such a score by estimating livestock GHG emissions, specifically from enteric fermentation and manure management, using TAPE data collected from smallholder farms in Kenya's Nandi and Bomet counties. Emission factors (EFs) derived from local studies were applied to improve accuracy of the GHG emission score, achieving a level of specificity comparable to Intergovernmental Panel on Climate Change (IPCC) Tier II methods. TAPE results showed correlations between total livestock emissions as well as milk-based emission intensity (EI) of cattle and the agroecological indicators: Efficiency, Recycling, and Resilience.
Discussion: The correlations varied in direction and magnitude, with the strongest relation found for Recycling and EI. Our findings demonstrate (1) the feasibility of integrating a GHG emission estimation into TAPE, and (2) highlight its potential as a tool for identifying synergies and tradeoffs between agroecological performance, emissions and emission intensities.

KEYWORDS

emission factors, IPCC, livestock, livestock systems, manure management, resilience

1 Introduction

The agricultural sector faces mounting pressure to contribute to the achievement of the Sustainable Development Goals (SDGs) while operating within the limits of planetary boundaries (Bicksler et al., 2023; Giller et al., 2021; Rockström et al., 2009; Wezel et al., 2020). At the same time, agriculture is a major driver of global environmental change, including greenhouse gas (GHG) emissions (Tubiello et al., 2014). In response to these intersecting challenges, numerous alternative approaches have emerged to promote a more sustainable and equitable Agri-food system.

Among these, agroecology has gained increasing recognition for its holistic approach to food system transformation. It integrates ecological principles with social and economic dimensions such as the co-creation of knowledge, participatory governance, and strengthened linkages between producers and consumers (Gliessman, 2018). As described by Wezel et al. (2020), the 10 elements and 13 principles of agroecology alongside the five levels of food system transformation provide a comprehensive framework for understanding and guiding action toward systemic change.

Until recently, the contribution of agroecology to meeting SDGs remained under-explored, in part due to fragmented evidence arising from heterogeneous methodologies. Consequently, the Food and Agriculture Organization (FAO) developed the Tool for Agroecology Performance Evaluation (TAPE) (Mottet et al., 2020) to overcome this bottleneck. In brief, TAPE collects harmonized data at the farm or household level, with supplementary information at the regional scale, and is structured into sequential steps. Step 1 assesses the Characteristics of Agroecological Transitions (CAET), based on the 10 elements of agroecology (Barrios et al., 2020). These are assessed in a qualitative, survey, by three or four multiple choice questions (Mottet et al., 2020, Supplementary material), resulting in a score of 1-100 for every element, where CAET is defined by the mean of the 10 scores. Step 2 evaluates the farm performance along key SDG-related dimensions, such as environmental, social, and economic sustainability, through qualitative and quantitative questions on a farm/household level, evaluated through more complex formulas, with outputs that can be summarized at the community or territorial scale. Although, Mottet et al. (2020) recommended the inclusion of GHG emissions as a context-specific indicator within Step 2′s environmental dimension, this component has, so far, not been implemented.

Livestock systems are central to agricultural livelihoods in Africa, especially for smallholder farmers, where they contribute to income and food security as well as providing resilience against climate shocks (Acosta et al., 2021; Ng'ang'a et al., 2016). Due to population growth and an increase in average income, there is an increasing demand for animal-source foods (Herrero et al., 2013). The market for livestock products, coupled with the benefits farmers get from livestock, is driving the trend toward an increased environmental footprint for consumers and producers (Erdaw, 2023). Livestock greenhouse gas emissions in Africa are often assumed to exceed global averages–particularly for emission intensities (EI)-caused by suboptimal livestock management and inconsistent feed availability and quality (Nkonya et al., 2016). Such assumptions frequently rely on generalized arguments as well as outdated data (Ndung'u et al., 2022). In response, several African countries have initiated efforts to quantify region-specific emissions factors (EFs), for national climate reporting under the United Nations Framework Convention on Climate Change (UNFCCC) to fulfill commitments to the Paris Agreement (Paris Climate Agreement | UNFCCC, 2015).

Simultaneously, agroecological farming systems are posited to enhancing livestock productivity and resilience to climate variability while reducing GHG emissions especially within smallholder contexts in low- and middle-income countries (LMICs) (Dittmer et al., 2023). As such, they offer a unique opportunity to support climate mitigation and adaptation goals while contributing to rural development (Bezner Kerr et al., 2023; Snapp et al., 2021). Thus, smallholder farmers are increasingly recognized as actors in climate change mitigation through productivity and efficiency improvements (Ndung'u et al., 2018). Recent empirical work from smallholder farming systems in Western Kenya (Ndung'u et al., 2018, 2021) provided farm-specific EFs for enteric fermentation in smallholder settings. These same farms were later assessed using TAPE, including supplemental questions on manure management. Through the integration of the collected datasets from the same cohort a unique opportunity arose, namely to estimate livestock-specific GHG emissions with TAPE for the first time.

To address the disconnect between agroecological performance assessment and GHG emissions reporting, this study aimed at estimating livestock GHG emissions through TAPE data and subsequently to develop a methodology for a livestock-specific emission score for TAPE. The proposed score focuses on enteric fermentation and manure management emissions, while excluding soil-related and off-farm (upstream) emissions, such as those from feed production, transport, and input manufacturing, which largely occur beyond the farm gate. We hypothesized that the derived values for livestock related GHG emission are better than Tier I estimates.

Our study further aimed at better understanding livestock GHG emissions from smallholder farms in East Africa to support the further development of TAPE as a multi-dimensional agroecological impact assessment tool. We hypothesized that greater use of agroecological methods will lead to lower GHG emission intensities (EI), while at the same time providing greater resilience against stresses.

2 Methods

2.1 Study data and area

Greenhouse gas emissions data were obtained from smallholder farms in Nandi and Bomet counties, Kenya. These data were originally collected in 2016 and are described in detail in (Ndung'u et al., 2022, 2021, 2018). Agroecological characteristics of the same farms were assessed in 2021 using TAPE, as described in Merbold et al. (in preparation)[1]. The TAPE surveys included 102 households (Figure 1), of which 51 (20 in Bomet and 31 in Nandi) responded to an additional question: *"How do you store the collected manure?"* This question was not part of the standard TAPE questionnaire, but was essential for the GHG emission estimation as otherwise the calculations could not have been performed. All GHG emission calculations were based on the 2019 IPCC guidelines (IPCC, 2019, Ch. 10). To enable its integration into Step 2 of the TAPE framework, as proposed by Mottet et al. (2020), the IPCC methodology was adapted to a household-level assessment.

Among the 51 households that answered the one additional question on manure storage in the TAPE questionnaire, 40

1 Merbold, L., Mottet, A., Baumgartner, S., Felder, S., Herzog, Jeanneret, P., et al. (in preparation). *Agroecological Assessment of Smallholder Farming Systems in East Africa: Implications for Biodiversity*. in preparation.

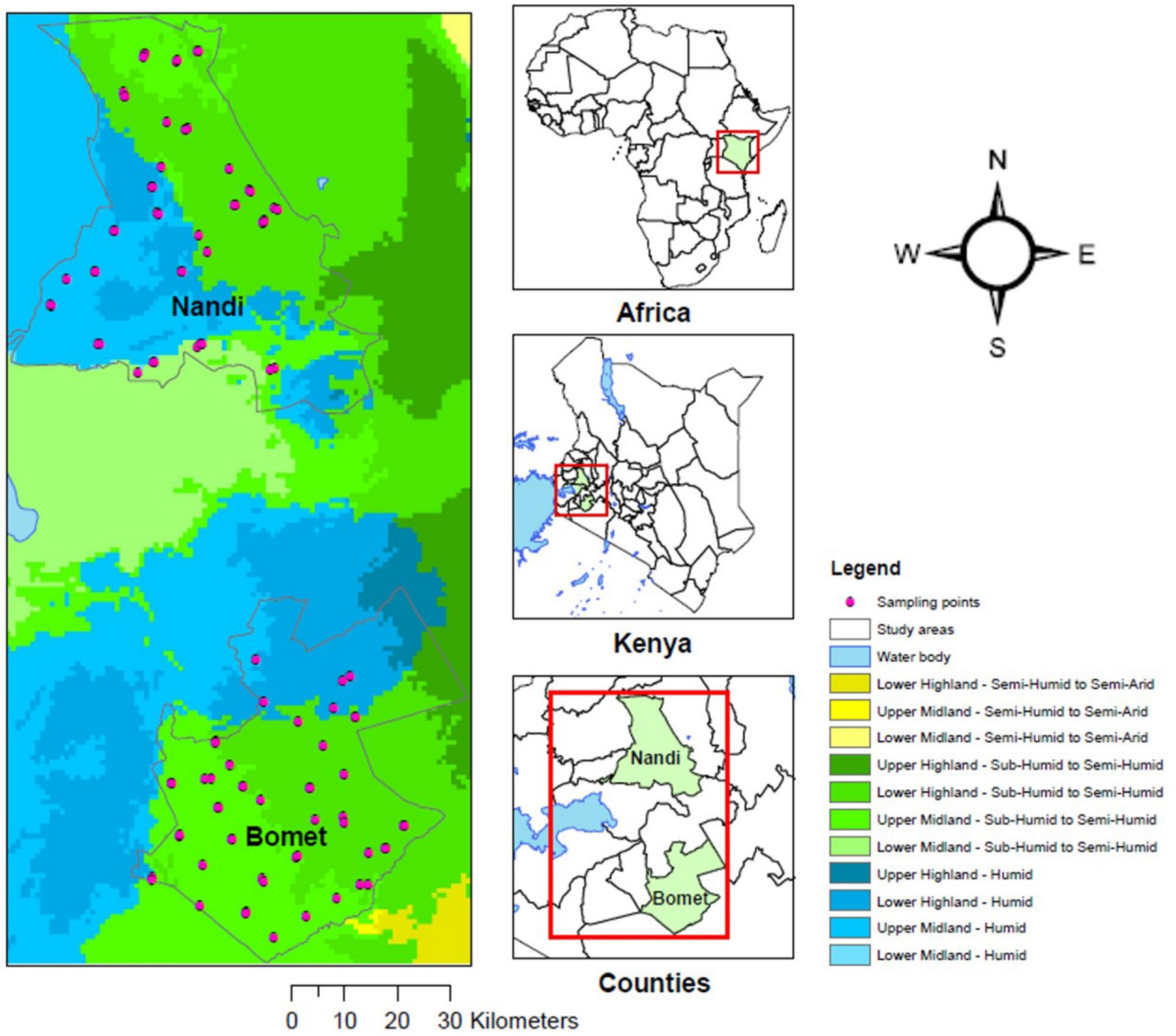

FIGURE 1
A map showing the location of Nandi and Bomet. The red dots show the random GPS points across the counties to which smallholder farms were sampled. Derived from Merbold et al. (in preparation)[1].

overlapped with those for which detailed farm-level GHG emission data were available from Ndung'u et al. (2022, 2021, 2018). This subset of 40 households was used for validating the proposed emission score methodology in terms of enteric fermentation. Due to the temporal mismatch between the two datasets of Ndung'u et al. (2022, 2021, 2018) and Merbold et al. (in preparation)[1] the herd sizes differed (Wilcoxon signed rank test $V = 502.5$, $p < 0.001$, with median values of 8 IQR = 5.5 for Ndung'u et al. (2022, 2021, 2018) and median values of 5 IQR = 4 for Merbold et al. (in preparation)[1] even though pertaining to the same farms. For this reason, the emissions were only compared for cattle. For interaction between agroecological performance indicators and GHG emissions the full subset ($n = 51$) was used.

2.2 Comparison of the subsample

We compared the farms of our study (subsample; $n = 51$) with the remaining farms ($n = 51$) of the full TAPE survey and which were also part of the studies carried out previously (Goopy et al., 2018; Ndung'u et al., 2021; Merbold et al., in preparation[1]) on structural, household, livestock, and production variables (area, household size, crop area, income, numbers of cattle, goats, sheep, crop, and cattle milk production). Because all variables were non-normally distributed, we reported medians and interquartile ranges (IQR) and used Wilcoxon rank–sum tests with Hodges–Lehmann (HL) estimates of the median difference and 95% confidence intervals. *P*-values were adjusted for multiple comparisons using the Benjamini–Hochberg procedure.

2.3 Climate and farming systems

The study was conducted in Nandi and Bomet counties in Western Kenya, both characterized by a bimodal rainfall pattern. This climate supports two cropping seasons per year: the short rains (November to January), followed by a hot dry season (February to April); and the long rains (May to July), followed by a cold dry season (August to October). Annual precipitation ranges from 950 to 1,500 mm, with altitudes ranging between 1,800 and 2,400 m above sea level (Ndung'u et al., 2018).

Farming systems in the region are best described as mixed crop-livestock systems. The mean farm size under active agricultural production was 1.2 ha (SD = 0.97). Major crops included maize (*Zea mays*), coffee (*Coffea arabica*), tea (*Camellia sinensis*), sugarcane (*Saccharum officinarum*), and beans (*Phaseolus vulgaris*). Farms also typically featured small plots of bananas (*Musa spp.*) and a variety of short-cycle vegetables, such as yams (*Dioscorea* sp.), sweet potatoes (*Ipomoea batatas*), onions (*Allium cepa*), and leafy greens like cabbages and kale (*Brassica* sp.).

In addition to fodder crops, with species such as Napier grass (*Pennisetum purpureum*) and Rhodes grass (*Chloris gayana*) were commonly cultivated under cut-and-carry systems to support livestock feeding. The typical livestock inventory included cattle, sheep, goats, and poultry, primarily composed of mixed local and improved breeds (Merbold et al., in preparation)[1].

2.4 Calculation of greenhouse gas emissions

GHG emission estimations for the emission score were based on the Intergovernmental Panel on Climate Change (IPCC, 2019) 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories, specifically Chapter 10 on emissions from livestock and manure management (Calvo Buendia et al., 2019). The IPCC provides a tiered methodological framework, where Tier I uses global default values and broad assumptions, and Tiers II and III incorporate increasingly detailed, region-specific data and complex modeling approaches to improve accuracy.

Although a Tier I approach was selected to ensure compatibility with available TAPE data, the emission score presented here reflects an *improved Tier I estimation*. This enhancement was made possible through the integration of emission factors (EFs) and livestock weights derived from previous Tier II studies conducted in the study region (Goopy et al., 2021; Leitner et al., 2021; Ndung'u et al., 2021). These regionalized parameters allowed for greater specificity and context relevance while maintaining the structural simplicity of Tier I methods. In summary, Tier I is the most simple approach and Tier II would encompass all the necessary information (including herd structure). TAPE survey data does not allow for full Tier II calculation, however it allows for a much better Tier I estimation.

GHG emissions were estimated using both the standard Tier I method and the improved Tier I emission score. These estimates were then compared to Tier II benchmarks for enteric fermentation in cattle as reported by Ndung'u et al. (2018) to assess the performance of the improved approach.

The IPCC equations were adapted to operate at the farm scale, rather than the national level. Specifically, the Animal Waste Management System (AWMS) factor—which provides country-level averages of manure management practices—was removed. Instead, TAPE-supplied data on farm-level manure management systems enabled direct matching with specific EFs, thereby eliminating the need for the AWMS factor and improving the resolution of manure management emission estimates.

This study focused on emissions from methane (CH_4) produced through enteric fermentation, and both methane and nitrous oxide (N_2O) emissions associated with manure management. The latter included direct N_2O emissions, as well as indirect N_2O emissions from nitrogen volatilization and leaching. Emissions were calculated for cattle, sheep, and goats, representing the dominant livestock species on the surveyed farms. Other livestock species were excluded due to their negligible contribution to overall GHG emissions at farm level. When localized data were unavailable—for instance, cattle gender—the mean value of available EF subcategories (e.g., dairy and other cattle) was used. All EF values were sourced from IPCC (2019) tables for warm-climate, low-productivity systems in sub-Saharan Africa (SSA) and are reported in the Supplement.

2.4.1 Methane emissions from enteric fermentation

Methane (CH4) emissions from enteric fermentation were estimated using Equation 1 (IPCC, 2019, Ch. 10). For the Tier I calculation, default emission factors (EFs) were obtained directly from the IPCC (2019) tables, representing warm-climate, low-productivity systems.

$$\mathbf{CH_{4\ ef}} = \sum \mathbf{EF} \times \mathbf{N} \tag{1}$$

$CH_{4\ ef}$ = methane emissions from enteric fermentation
EF = Emission factor for the defined livestock population
N = livestock population

In the improved Tier I emission score estimation, region-specific EFs were applied. For cattle, age-specific EFs derived from Ndung'u et al. (2021) were used to better reflect physiological variation within the herd. For sheep and goats, herd-dynamic-weighted EFs were calculated based on the distributions reported in Goopy et al. (2021), allowing for more precise estimations across livestock age and gender classes. A full list of all EFs used in this study is provided in Supplementary Table 1.

2.4.2 Methane emissions from manure management

Methane (CH4) emissions from manure management were estimated using Equation 2. Similar to the emission from enteric fermentation, for the Tier I estimation, all input parameters—including emission factors (EFs), volatile solid excretion rates, and default weights—were sourced directly from IPCC (2019) tables for warm-climate, low-productivity systems.

$$\mathbf{CH_{4\ mm}} = \sum \mathbf{N} \times \mathbf{VS_{rate}} \times \frac{\mathbf{TAM}}{\mathbf{1000}} \times \mathbf{365} \times \mathbf{EF} \quad (2)$$

CH_4 mm = methane emissions from manure management
TAM = Typical animal mass [kg]
N = livestock population
VS_{rate} = Volatile Solids excretion rate (per 1000 kg animal mass per day)
EF = Emission factor for methane emissions from manure management

To improve the accuracy of the emission score, region-specific animal weights from Ndung'u et al. (2021) and Goopy et al. (2021) were incorporated. These weights were disaggregated by cattle age group and county, allowing for more refined estimation. While the default Tier I EFs were used as a baseline, recent findings by Leitner et al. (2021) reported methane and nitrous oxide emissions from cattle manure heaps with typical feeding practices from smallholder farms in the east African highlands. These findings were lower than the available IPCC (2019) values. The same study provided a regional EF for solid manure storage from which we derived a factor by dividing the regional EF for solid manure storage (Leitner et al., 2021) by the IPCC (2019) Tier I EF for solid manure storage. All the system-specific EF's from Tier I were multiplied by this factor for regional adjustment. The adjusted EFs for each manure storage system are provided in Supplementary Table 2. Volatile solid excretion rates used in the calculations were consistent across both Tier I and improved approaches and are presented in Supplementary Table 3. Animal weights applied in the calculations are detailed in Supplementary Table 4. For sheep and goats, a uniform EF of 0.0215 kg CH_4 head^{-1} day^{-1} was applied, independent of manure management systems as reported by Zhu et al. (2018).

2.4.3 Nitrous oxide emissions from manure management

Nitrous oxide emissions from manure management were categorized into three pathways: (i) direct emissions from on-farm manure storage, (ii) indirect emissions due to nitrogen leaching, and (iii) indirect emissions due to nitrogen volatilization. These emissions were estimated using Equations 3–5.

$$\mathbf{N_2O_{D(mm)}} = \sum \left(\mathbf{N} \times \mathbf{N_{rate}} \times \frac{\mathbf{TAM}}{\mathbf{1000}} \times \mathbf{365} \times \mathbf{EF} \right) \times \frac{\mathbf{44}}{\mathbf{28}} \quad (3)$$

$N_2O_{D(mm)}$ = direct N_2O emissions from manure management
N = livestock population
N_{rate} = average N excretion per head of species
TAM = Typical animal mass [kg]
EF = Emission factor for direct N_2O from manure management systems
44/28 = conversion of N_2O - N emissions to N_2O emissions

$$\mathbf{N_2O_{G(mm)}} = \sum \left(\mathbf{N} \times \mathbf{N_{rate}} \times \frac{\mathbf{TAM}}{\mathbf{1000}} \times \mathbf{365} \times \mathbf{Frac_{Gas}} \right) \times \mathbf{EF_4} \times \frac{\mathbf{44}}{\mathbf{28}} \quad (4)$$

$N_2O_{G(mm)}$ = indirect N_2O emissions due to volatilization of N from manure management
N = livestock population
N_{rate} = average N excretion per head of species
TAM = Typical animal mass [kg]
$Frac_{Gas}$ = fraction of managed manure nitrogen per livestock category that volatilizes as NH_3 and NO_x in the manure management system
EF4 = Emission factor for indirect N_2O from atmospheric deposition of nitrogen on soils and water surfaces
44/28 = conversion of N_2O - N emissions to N_2O emissions.

$$\mathbf{N_2O_{L(mm)}} = \sum \left(\mathbf{N} \times \mathbf{N_{rate}} \times \frac{\mathbf{TAM}}{\mathbf{1000}} \times \mathbf{365} \times \mathbf{Frac_{Leach}} \right) \times \mathbf{EF_5} \times \frac{\mathbf{44}}{\mathbf{28}} \quad (5)$$

$N_2O_{L(mm)}$ = indirect N_2O emissions due to leaching of N from manure management
N = livestock population
N_{rate} = average N excretion per head of species
TAM = Typical animal mass [kg]
$Frac_{Leach}$ = fraction of managed manure nitrogen per livestock category that is leached from the manure management system
EF5 = Emission factor from nitrogen leaching and runoff
44/28 = conversion of N2O - N emissions to N2O emissions

For the improved emission score estimation, the emission factor (EF) for direct N_2O emissions from solid storage systems was adjusted based on region-specific findings. Leitner et al. (2021) reported lower direct N_2O EFs for solid storage systems in the study region compared to IPCC (2019) default values. Consequently, all relevant EFs were downscaled with the same procedure as for the methane manure EF's. Adjusted values are provided in Supplementary Table 5. For sheep and goats, a constant EF of 0.0125 kg N_2O head^{-1} year^{-1} was applied, irrespective of manure management system, as suggested by Zhu et al. (2024).

2.4.4 Total livestock emissions and emission per household

To convert methane and nitrous oxide emissions into carbon dioxide equivalents, the Global Warming Potential over a 100 year time horizon (GWP100) was applied (IPCC, 2019). The characterization factors used, were 25 for CH_4 and 298 for N_2O, respectively, Equation 6. Total livestock emissions per household were calculated by summing the CO_2-equivalents of the total livestock emissions for every animal within the household. Similarly, emissions from manure management were aggregated and converted to CO_2-equivalents using Equation 7. For a standardized comparison across cattle goats and sheep, as well as farms of varying size the tropical Livestock Unit (LSU) was used (IPCC, 2019). Local weights, provided by Ndung'u et al. (2018) and Goopy et al. (2021), allowed for a further distinguished local LSU for calves and heifers. The LSU values are presented in

Supplementary Table 4. The total household LSU was calculated as a sum of the LSU values of every animal within the household. The enteric fermentation, manure management and total livestock emissions of every household were then divided by the total household LSU to get the unit of [kg CO_2-eq household^{-1} LSU^{-1} year^{-1}] which was used for the correlation matrix. Emission intensities (EI) were calculated by combining TAPE survey data with the estimated GHG emissions derived from the emission score. This analysis was restricted to cow milk as it was the only production data available through TAPE, therefore only cattle emissions were used. EIs were calculated at the household level by dividing total livestock emissions (in CO_2-eq) by the corresponding total annual milk production (in liters) for each household.

$$\textbf{Livestock} = (\mathbf{CH_{4\,ef}} \times \mathbf{25}) + (\mathbf{CH_{4\,mm}} \times \mathbf{25}) + \left(\mathbf{N_2O_{D(mm)}} \times \mathbf{298}\right) + \left(\mathbf{N^2O_{G(mm)}}\ (\mathbf{mm}) \times \mathbf{298}\right) + \left(\mathbf{N^2O_{L(mm)}} \times \mathbf{298}\right) \quad (6)$$

$$\textbf{MM} = (\mathbf{CH_{4\,mm}} \times \mathbf{25}) + \left(\mathbf{N^2O_{D(mm)}} \times \mathbf{298}\right) + \left(\mathbf{N^2O_{G(mm)}}\ (\mathbf{mm}) \times \mathbf{298}\right) + \left(\mathbf{N^2O_{L(mm)}} \times \mathbf{298}\right) \quad (7)$$

Livestock = Total livestock emissions in CO_2 equivalent

MM = Total manure management emissions in CO_2 equivalent

25 = Global warming potential factor for methane (CO_2 equivalents)

298 = Global warming potential factor for nitrous oxide (CO_2 equivalents)

2.5 TAPE step 1 scores

The detailed methodology for calculating TAPE Step 1 scores is described in Gilgen et al. (2023). In brief, a score is calculated for each of the 10 elements of agroecology (Mottet et al., 2020). Each score is derived from responses to three or four multiple-choice questions, with each response assigned a value between one and four. The final score for each agroecological element is calculated as the scaled mean of these values, resulting in a score ranging from one to 100. For example, the Diversity element aggregates information on crop, livestock, and tree (or other perennial) diversity, as well as the income diversity—assigning higher scores to farms exhibiting greater overall diversity. The Characterization of Agroecological Transition (CAET) score is calculated as the mean of the scores for all 10 elements.

2.6 Data analysis

All statistical analyses were conducted using R version 4.4.3 (R Core Team, 2025). Data were tested for normality using the Shapiro–Wilk test. Given the non-normal distribution of the emission and household data, non-parametric tests were employed throughout. A p-value of <0.05 was chosen for significance.

To compare GHG emissions between the Tier I, Tier II, and improved emission score methods, the Mann–Whitney U test was used. As the Tier I method produces a single constant value, it was assumed to differ from the other methods by design. Comparisons of emission estimates between counties (Nandi and Bomet) were also conducted using the Mann–Whitney U-test.

The Kruskal–Wallis test was applied to assess differences in emissions across individual households. Correlations between GHG emissions and TAPE Step 1 scores were evaluated using Spearman's rank correlation coefficient, due to the ordinal nature of the agroecological indicators and the non-parametric distribution of the emissions data. To account for multiple testing and to avoid false positives, we adjusted p-values using the Benjamini–Hochberg False Discovery Rate (FDR) procedure (Box, 1953). For transparency and comparability, we report both unadjusted and adjusted p-values. We emphasize on the magnitude and direction of the correlation coefficients.

3 Results

3.1 Comparison of the subsample

Medians and interquartile ranges (IQRs) for area, crop area, income, production and livestock numbers were similar between the subsample and the remaining farms (Table 1). After Benjamini–Hochberg correction, the variables showing a statistically significant difference were milk production and goats, with higher values in our study subsample. This indicates that, apart from a tendency toward higher milk production and more goats, the subsample is broadly representative of the full sample in terms of the main structural and livestock characteristics considered.

3.2 GHG emission estimates from enteric fermentation

The Tier I method yielded uniform estimates of 57 kg CH_4 head^{-1} year^{-1} for all cattle, significantly differing from both the emission score and Tier II methods. In contrast, the emission score produced a range of 18.3–43.6 kg CH_4 head^{-1} year^{-1} (IQR = 17.7), while the Tier II method showed a wider range of 6.2–162.3 kg CH_4 head^{-1} year^{-1} (IQR = 24.1). No significant difference was observed between the emission score and Tier II estimates ($W = 102165$, $p = 0.269$), supporting the validity of the emission score as a valid estimation method (Figure 2). All subsequent analyses are based on our improved emissions estimates.

Enteric fermentation accounted for 72.9% of livestock related CH_4 emissions across all farms. Cattle contributed most of these emissions (89.7%), while comprising of 54% of the herd, with a median emission value of 43.5 kg CH_4 head^{-1} year^{-1} (IQR = 17.7). Sheep and goats showed substantially lower CH_4 emissions from fermentation emissions (median of 4.6 kg CH4 head^{-1} year^{-1} (IQR = 1.2)) with sheep being 32% of the herd and goats 13%. Per household a median of 107.9 kg CH4 LSU^{-1} year^{-1} (IQR = 159.8) was produced. No significant differences in enteric fermentation emissions (kg CH_4 head^{-1} year^{-1}) were observed between counties ($W = 568$, $p = 1.000$).

TABLE 1 Comparison of the farms included in the TAPE study where the emission score was calculated, referred as subset farms ($n = 51$) and, where the emission score could not be calculated, referred as TAPE farms ($n = 51$), IQR is the interquartile range, HL are Hodges-Lehmann median difference, BH are the Benjamini-Hochberg adjusted p-values (Goopy et al., 2018; Ndung'u et al., 2021; Merbold et al., in preparation[1]).

Variable	Median subset farms	IQR subset farms	Median TAPE farms	IQR TAPE farms	p-value Wilcoxson	HL difference	p-values BH
Area [ha]	1.21	0.765	0.81	1.38	0.122	0.280	0.220
Area for crop production [ha]	1.01	0.83	0.81	1.02	0.299	1.9	0.385
Household members	8	4	7	3	0.039	1	0.188
Income [KES]	261,050	335,736	297,200	396,527	0.342	44,000	0.385
Sheep	0	0.5	0	0	0.149	0.00001	0.223
Goats	0	5	0	0.5	0.020	0.00003	0.0912
Cattle	4	5	4	3	0.056	1	0.127
Cow milk production (kg)	4,910	4,192	2,745	3,050	0.0003	2,135	0.003
Crop production (kg)	6,686	13,994	5,360	12,110	0.454	997	0.454

With Hodges–Lehmann median differences, 95% confidence intervals, Wilcoxon rank–sum p-values (Benjamini–Hochberg adjusted).

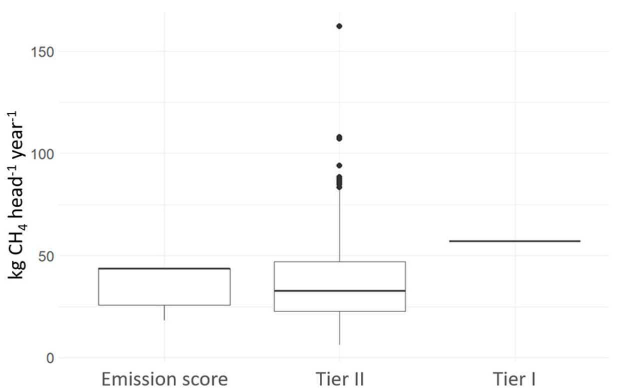

FIGURE 2
Boxplot comparison of methane emissions (kg CH_4 head^{-1} year^{-1}) from enteric fermentation estimated using three different methods. Each box represents the distribution of emissions for cattle under the respective method.

Manure management was responsible for 27.2% of total livestock emissions, with 75.7% of the manure management emissions attributed to CH4 and 24.3% to N_2O. Cattle manure was the dominating source, accounting to 99.2% of manure management emissions. Median GHG emissions for cattle manure were 1,094.8 kg CO_2-eq head^{-1} year^{-1} (IQR = 1802.3), while sheep and goat manure produced 18.9 kg CO_2-eq head^{-1} year^{-1} (IQR = 8.4). On a per-household basis, the median emission was 566 kg CO_2-eq LSU^{-1} year^{-1} (IQR = 2122). Median total livestock emissions per household were 3,585 kg CO_2-eq household^{-1} LSU^{-1} year^{-1} (IQR = 6175).

No significant differences were observed between counties in household-level or per-animal emissions across cattle, sheep, or goats, for herd composition, enteric fermentation, manure management, or total livestock emissions.

3.3 Relationship between the 10 elements of agroecology and the emission score

The enteric fermentation, manure management and livestock emissions per household (kg CO_2-eq household^{-1} LSU^{-1} year^{-1}) as well as the Emission Intensity for cow milk, were compared to the scores of the 10 elements of agroecology, calculated in TAPE step 1 (Figure 3). With the Benjamini–Hochberg False Discovery Rate (FDR) adjusted p-values only few of the correlations were significant ($p > 0.05$) as the correlation with emission metrics were moderate (Supplementary Table 7). We continued with the unadjusted p-values (Supplementary Table 8) interpreting the correlations as indicative, exploratory patterns rather than as confirmatory evidence of strong associations. This implies that not all statistically significant correlations may reflect true associations, as some may result from chance due to multiple testing. The Step 1 scores moderate correlations to the normalized livestock emissions pe farm-household. Notably in the Diversity, Synergy (where a Type 1 error is probable, as they showed low correlations not consistent across emissions), Efficiency, Circular and Solidarity Economy score as well as the overall Characterization of Agroecological Transition (CAET) score. For EI our results show predominantly negative correlations ($p < 0.05$) to the elements Circular and Solidarity Economy, Resilience and Recycling. The Efficiency score showed a positive significant correlation to EI.

4 Discussion

4.1 Evaluation of the proposed TAPE emission score

Our results demonstrate that TAPE survey data can serve as a valuable source for estimating livestock GHG emissions. For enteric fermentation, the application of region-specific emission factors (EFs) enables estimation accuracy consistent with Tier II methodologies (Ndung'u et al., 2022). Regarding GHG emissions

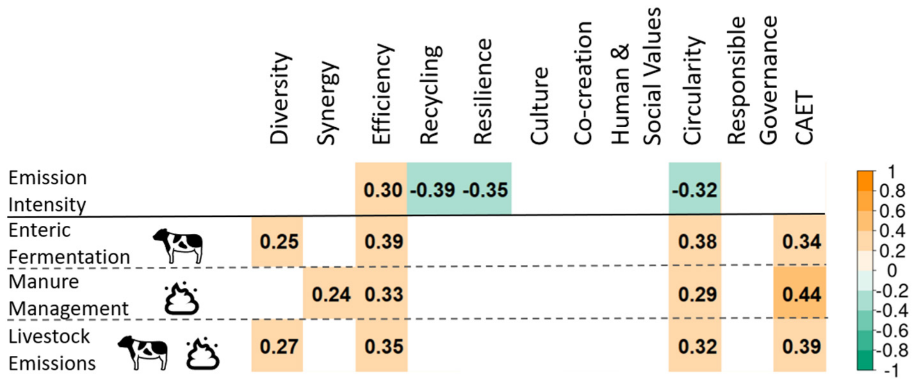

FIGURE 3
Results of the Spearman rank correlations between livestock emissions [kg CO_2-eq household^{-1} LSU^{-1} year^{-1}] as well as EI (only for cattle) [CO_2-eq. kg milk^{-1} hosuehold^{-1}] and TAPE step 1 scores ($n = 51$). Only significant correlations are shown with the unadjusted p-values of $p < 0.05$.

originating from manure, a direct comparison was not possible in our case since no existing manure management studies were conducted on the same farms. Nevertheless, the estimated total livestock emissions (enteric fermentation and manure) align well with previous findings from the region—both for cattle (Kiggundu et al., 2019; Leitner et al., 2021; Ndung'u et al., 2022; Scholtz et al., 2023; Zhu et al., 2024, 2018) and for small ruminants (Goopy et al., 2021; Zhu et al., 2024, 2018).

In our model, higher emissions per livestock unit (LSU) for enteric fermentation are associated with herds composed predominantly of older cattle (Ndung'u et al., 2022). For manure management, above median emissions per LSU result from the use of liquid slurry or pit storage systems, in contrast to lower-emission practices such as daily field spreading or solid storage. Farms with lower emissions per LSU generally maintain younger cattle herds or rely solely on small ruminants without permanent manure management infrastructure, typically spreading manure directly onto fields.

The approach presented here reflects current knowledge and yields results that are statistically indistinguishable from Tier II estimates in terms of enteric fermentation (Ndung'u et al., 2021). Yet, the broader distribution of emission values observed in Tier II studies (Figure 2, Ndung'u et al., 2021) may better reflect the heterogeneity of farming systems in the region. This is because Tier II methods—both for enteric fermentation and manure management—incorporate additional values such as feed intake, detailed herd structure amongst other data impacting livestock emissions directly. In contrast, our approach assigns a constant EF for all cattle within a given age and region category. In Tier II methodologies, EF values for enteric fermentation would vary depending on feed availability, diet composition and locomotion (Ndung'u et al., 2018).

Given the multi-indicator nature and simplicity of TAPE, collecting detailed feed data is impractical caused by the time and labor demand. As a result, the emission score relies on existing Tier II studies within the target region and will inherently be less capable of capturing the full range of emissions variability if such data are not available.

Incorporating livestock gender into the TAPE survey would represent a meaningful improvement in estimation precision, allowing for better alignment with real herd structures and consequently more accurate representation of livestock-related emissions. This distinction is explicitly recognized in IPCC methodologies, as emission outputs differ considerably between animal classes (e.g., bulls vs. dairy cows).

Our study represents a first step in developing a livestock-specific emission score within the TAPE framework where there are some considerations that need to be considered when interpreting emission estimates generated through this approach. TAPE collects data at a single point in time, which may not capture seasonal variability in livestock numbers or manure management practices—factors known to influence GHG emissions (Leitner et al., 2024). Furthermore, larger external shocks, such as climatic extremes, may result in substantial livestock losses that are not reflected in point-in-time assessments (Niles and Salerno, 2018). Also, the current emission score version focuses exclusively on direct emissions from enteric fermentation and manure management. This proposed methodology is particularly applicable to mixed crop–livestock systems, where animal-related emissions dominate overall GHG outputs. Accordingly, caution is advised when applying the emission score outside of such contexts. Emissions from other relevant sources—such as soil processes, feed production, and energy use—are not yet included. Furthermore, many mitigation opportunities lie in soil processes through carbon sequestration (Harrison et al., 2021). Practices such as agroforestry and organic farming are widely associated with increased soil carbon stocks and reduced N_2O emissions, often without negatively affecting crop yields (Guenet et al., 2021; Leippert et al., 2020; Tamburini et al., 2020). Incorporating soil-based emissions and carbon sequestration potential into the TAPE framework is essential before the emission score can be fully operationalized. The further development of TAPE would help and is urgently needed to close the knowledge gap between agroecology and climate mitigation and adaption, amid growing evidence of its benefits (Owen, 2020; Snapp et al., 2021), as the intersection between agroecology and emissions–particularly in LMIC–remains understudied and hindered by fragmented data (Connor, 2018; Paul et al., 2020; Snapp et al., 2021).

4.2 Agroecological elements in relation to the emissions score

The lack of statistically significant correlations after FDR correction does not imply the absence of any relationship between agroecological indicators and emissions; rather, it reflects limited statistical power in combination with multiple testing. In line with this we use the correlations to describe the direction and relative strength of the associations. Our results show both positive and negative correlations between total household livestock emissions per LSU, EI and the CAET score, implying that some agroecological practices could result in higher emissions, while others would aid mitigation. The positive correlations could be interpreted as a tradeoff, yet it is essential to consider the GHG emission baseline of the farms observed-low productive smallholder subsistence farming systems. Within these, any increase in farm productivity while keeping animal numbers constant will lead to higher emissions (Ndung'u et al., 2018; Merbold et al., in preparation[1]). Simultaneously, emission intensities, a measure of efficiency will decline, which is consistent with our observed positive GHG–efficiency correlations,. Previous studies have shown that yield stability and the use of this yield for consistent livestock feeding reduce milk EI (Ndung'u et al., 2022). To underline this finding, our data show negative correlations between GHG emissions and the Recycling score, reflecting feed use (Leippert et al., 2020; Tamburini et al., 2020) as well as the Resilience score, reflecting yield stability (Altieri et al., 2015). According to Gliessman (2016) framework, lower-level agroecological practices focus on improving productivity, whereas higher-level practices involve system redesign and social dimensions such as Recycling, Resilience, and Circular and Solidarity Economy. Our data show positive correlations between GHG emissions and lower-level efficiency scores, but negative correlations with higher-level scores. This suggests that once efficiency gains are achieved, progressing toward higher levels of agroecological transition is expected to mitigate GHG emissions while maintaining production.

Importantly, understanding the effectiveness of smallholder farms must also consider their vulnerability and resilience to climate-related shocks. There is growing evidence that agroecological practices support climate adaptation without compromising yields (Altieri et al., 2015; Snapp et al., 2021). Especially livestock, has shown to support overall environmental performance by enabling nutrient cycling, diversified income streams, and integrated production strategies (Oosting et al., 2025; Paul et al., 2020). Tanner et al. (2000) found that smallholders in Kenya valued the manure production function of cattle as more important than the milk production function, illustrating their overall concern for the environmental health of their farming system as the basis for sustained production. Livestock also increases farm household resilience, serving as an income and nutritional buffer in times of crop production shocks; and it serves as a status symbol and for cultural functions (Michalscheck et al., 2023; Udo et al., 2016). It is therefore important to assess livestock through a lens that accounts for the broader role of livestock in smallholder contexts-beyond the narrow goal of reducing livestock emissions alone (Adesogan et al., 2025).

5 Conclusion

Our findings demonstrate that TAPE survey data hold considerable potential for estimating livestock GHG emissions and thereby contribute to closing the knowledge gap between agroecology and climate impact assessment. The emission score developed in this study produced results statistically comparable to IPCC Tier II methodologies for enteric fermentation. However, it remains inherently less specific than full Tier II approaches due to structural constraints—particularly the absence of feed intake data—reflecting the simplified nature of the TAPE tool. The use of region-specific emission factors from previous Tier II studies enhances accuracy, yet the reliance on these external data sources underscores the need for localized calibration. Incorporating livestock gender into the TAPE framework would further improve precision but cannot fully resolve this limitation.

Before broader implementation, the emission score should be expanded to include other on-farm emission sources—most notably soil-based GHG emissions that are linked to feed production. These additions must be balanced with the need to maintain the simplicity and usability of the TAPE tool for rapid, multi-indicator assessments.

Crucially, any evaluation of GHG emissions in smallholder systems must be contextualized within the multifunctional role of livestock. Rather than focusing solely on emission reduction, assessments must recognize the broader environmental and livelihood contributions of livestock within agroecological practices.

The integration of the TAPE emission score is urgently needed to aid in closing the knowledge gap in the intersection of agroecology and GHG emissions. While further development is needed it offers a promising pathway to better link agroecological transitions with climate mitigation and adaptation outcomes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SP: Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. JJ: Methodology, Supervision, Writing – review & editing. PN: Writing – review & editing, Validation, Formal analysis, Investigation. MM: Formal analysis, Validation, Writing – review & editing, Supervision, Visualization. LM: Supervision, Validation, Visualization, Writing – review & editing, Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Writing – original draft.

Funding

The author(s) declared that financial support was received for this work and/or its publication. Funding for this study was received under the Solution-oriented Research for Development (SOR4D) programme, a joint funding instrument between the Swiss Agency for Development and Cooperation (SDC) and the Swiss National Science Foundation (SNSF), for the project "Circularity of Nutrients in Agroecosystems and co-benefits on animal and human health" (CIRNA, grant number 400440_217985). Furthermore, earlier collected data used in this project were funded by the German Federal Ministry for Economic Cooperation and Development (BMZ) and the German Technical Cooperation (GIZ) under the project: Programme for Climate Smart Livestock (PCSL, grant no: 2017.0119.2), and the International Fund for Agricultural Development (Award Number: 2000000994. In addition, the authors acknowledge funding received the CGIAR Science Programs on Sustainable Farming, Climate Action, and Sustainable Animal and Aquatic Food Systems, which are supported by contributors to the CGIAR Trust Fund. CGIAR is a global research partnership for a food-secure future dedicated to transforming food, land, and water systems in a climate crisis. The authors would like to thank all the help received from colleagues at ILRI's Mazingira Center. Open access funding by Agroscope.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1717931/full#supplementary-material

References

Acosta, A., Nicolli, F., and Karfakis, P. (2021). Coping with climate shocks: the complex role of livestock portfolios. *World Dev.* 146:105546. doi: 10.1016/j.worlddev.2021.105546

Adesogan, A. T., Gebremikael, M. B., Varijakshapanicker, P., and Vyas, D. (2025). Climate-smart approaches for enhancing livestock productivity, human nutrition, and livelihoods in low- and middle-income countries. *Anim. Prod. Sci.* 65:AN24215. doi: 10.1071/AN24215

Altieri, M. A., Nicholls, C. I., Henao, A., and Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agron. Sustain. Dev.* 35, 869–890. doi: 10.1007/s13593-015-0285-2

Barrios, E., Gemmill-Herren, B., Bicksler, A., Siliprandi, E., Brathwaite, R., Moller, S., et al. (2020). The 10 elements of agroecology: enabling transitions towards sustainable agriculture and food systems through visual narratives. *Ecosyst. People* 16, 230–247. doi: 10.1080/26395916.2020.1808705

Bezner Kerr, R., Postigo, J. C., Smith, P., Cowie, A., Singh, P. K., Rivera-Ferre, M., et al. (2023). Agroecology as a transformative approach to tackle climatic, food, and ecosystemic crises. *Curr. Opin. Environ. Sustain.* 62:101275. doi: 10.1016/j.cosust.2023.101275

Bicksler, A. J., Mottet, A., Lucantoni, D., Sy, M. R., and Barrios, E. (2023). The 10 elements of agroecology interconnected: making them operational in FAO's work on agroecology. *Elem. Sci. Anthr.* 11:00041. doi: 10.1525/elementa.2022.00041

Box, G. E. P., (1953). Non-normality and tests on variances. *Biometrika* 40, 318–335. doi: 10.1093/biomet/40.3-4.318

Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., et al. (Eds.) (2019). "Emissions from livestock and manure management," in *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 4* (Switzerland: IPCC).

Connor, D. J. (2018). Organic agriculture and food security: a decade of unreason finally implodes. *Field Crops Res.* 225, 128–129. doi: 10.1016/j.fcr.2018.06.008

Dittmer, K. M., Rose, S., Snapp, S. S., Kebede, Y., Brickman, S., Shelton, S., et al. (2023). Agroecology can promote climate change adaptation outcomes without compromising yield in smallholder systems. *Environ. Manage.* 72, 333–342. doi: 10.1007/s00267-023-01816-x

Erdaw, M. M. (2023). Contribution, prospects and trends of livestock production in sub-Saharan Africa: a review. *Int. J. Agric. Sustain.* 21:2247776. doi: 10.1080/14735903.2023.2247776

Gilgen, A., Felder, R., Baumgartner, S., Herzog, F., Jeanneret, P., S?chaud, R., et al. (2023). How to assess the agroecological status of Swiss farming systems? – application of the tool for agroecology performance evaluation (TAPE) and further development. *Agroscope Sci.* 172. doi: 10.34776/as172e

Giller, K. E., Hijbeek, R., Andersson, J. A., and Sumberg, J. (2021). Regenerative agriculture: an agronomic perspective. *Outlook Agric.* 50, 13–25. doi: 10.1177/0030727021998063

Gliessman, S. (2016). Transforming food systems with agroecology. *Agroecol. Sustain. Food Syst.* 40, 187–189. doi: 10.1080/21683565.2015.1130765

Gliessman, S. (2018). Defining agroecology. *Agroecol. Sustain. Food Syst.* 42, 599–600. doi: 10.1080/21683565.2018.1432329

Goopy, J. P., Ndung'u, P. W., Onyango, A., Kirui, P., and Butterbach-Bahl, K. (2021). Calculation of new enteric methane emission factors for small ruminants in western Kenya highlights the heterogeneity of smallholder production systems. *Anim. Prod. Sci.* 61, 602–612. doi: 10.1071/AN19631

Goopy, J. P., Onyango, A. A., Dickhoefer, U., and Butterbach-Bahl, K. (2018). A new approach for improving emission factors for enteric methane emissions of cattle in smallholder systems of East Africa – results for Nyando, Western Kenya. *Agric. Syst.* 161, 72–80. doi: 10.1016/j.agsy.2017.12.004

Guenet, B., Gabrielle, B., Chenu, C., Arrouays, D., Balesdent, J., Bernoux, M., et al. (2021). Can N_2O emissions offset the benefits from soil organic carbon storage? *Glob. Change Biol.* 27, 237–256. doi: 10.1111/gcb.15342

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

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M. C., Thornton, P. K., et al. (2013). Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc. Natl. Acad. Sci. U.S.A*. 110, 20888–20893. doi: 10.1073/pnas,0.1308149110

IPCC (2019). *Refinement to the Guidelines for National Greenhouse Gas Inventories*, eds. E. Calvo Buendia, K. Tanabe, A. Kranjc, J. Baasansuren, M. Fukuda, S. Ngariz, et al. Switzerland: IPCC.

Kiggundu, N., Ddungu, S. P., Wanyama, J., Cherotich, S., Mpairwe, D., Zziwa, E., et al. (2019). Greenhouse gas emissions from Uganda's cattle corridor farming systems. *Agric. Syst*. 176:102649. doi: 10.1016/j.agsy.2019.102649

Leippert, F., Darmaun, M., Bernoux, M. and Mpheshea, M. (2020). *The Potential of Agroecology to Build Climate-Resilient Livelihoods and Food Systems*. Rome: FAO and Biovision. doi: 10.4060/cb0438en

Leitner, S., Ring, D., Wanyama, G. N., Korir, D., Pelster, D. E., Goopy, J. P., et al. (2021). Effect of feeding practices and manure quality on CH_4 and N_2O emissions from uncovered cattle manure heaps in Kenya. *Waste Manag*. 126, 209–220. doi: 10.1016/j.wasman.2021.03.014

Leitner, S. M., Carbonell, V., Mhindu, R. L., Zhu, Y., Mutuo, P., Butterbach-Bahl, K., et al. (2024). Greenhouse gas emissions from cattle enclosures in semi-arid sub-Saharan Africa: the case of a rangeland in South-Central Kenya. *Agric. Ecosyst. Environ*. 367:108980. doi: 10.1016/j.agee.2024.108980

Michalscheck, M., Kizito, F., Kotu, B. H., Avornyo, F. K., Timler, C., and Groot, J. C. J. (2023). Preparing for, coping with and bouncing back after shocks. A nuanced resilience assessment for smallholder farms and farmers in Northern Ghana. *Int. J. Agric. Sustain*. 21:2241283. doi: 10.1080/14735903.2023.2241283

Mottet, A., Bicksler, A., Lucantoni, D., De Rosa, F., Scherf, B., Scopel, E., et al. (2020). Assessing transitions to sustainable agricultural and food systems: a Tool for Agroecology Performance Evaluation (TAPE). *Front. Sustain. Food Syst*. 4:579154. doi: 10.3389/fsufs.2020.579154

Ndung'u, P.W., Takahashi, T., du Toit, C.J.L., Robertson-Dean, M., Butterbach-Bahl, K., McAuliffe, G.A. (2022). Farm-level emission intensities of smallholder cattle (*Bos indicus*; *B. indicus–B. taurus* crosses) production systems in highlands and semi-arid regions. *Animal* 16:100445. doi: 10.1016/j.animal.2021.100445

Ndung'u, P. W., Bebe, B. O., Ondiek, J. O., Butterbach-Bahl, K., Merbold, L., and Goopy, J. P. (2018). Improved region-specific emission factors for enteric methane emissions from cattle in smallholder mixed crop: livestock systems of nandi County, Kenya. *Anim. Prod. Sci*. 59, 1136–1146. doi: 10.1071/AN17809

Ndung'u, P. W., Kirui, P., Takahashi, T., du Toit, C. J. L., Merbold, L., and Goopy, J. P. (2021). Data describing cattle performance and feed characteristics to calculate enteric methane emissions in smallholder livestock systems in Bomet County, Kenya. *Data Brief* 39:107673. doi: 10.1016/j.dib.2021.107673

Ng'ang'a, S. K., Bulte, E. H., Giller, K. E., Ndiwa, N. N., Kifugo, S. C., McIntire, J. M. (2016). Livestock wealth and social capital as insurance against climate risk: a case study of samburu county in Kenya. *Agric. Syst*. 146, 44–54. doi: 10.1016/j.agsy.2016.04.004

Niles, M. T., and Salerno, J. D. (2018). A cross-country analysis of climate shocks and smallholder food insecurity. *PLoS ONE* 13:e0192928. doi: 10.1371/journal.pone.0192928

Nkonya, E., Johnson, T., Kwon, H.Y., and Kato, E. (2016). "Economics of land degradation in Sub-Saharan Africa," in *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development*, eds. E. Nkonya, A. Mirzabaev, J. von Braun (Cham: Springer International Publishing), 215–259. doi: 10.1007/978-3-319-19168-3_9

Oosting, S. J., Crane, T. A., Notenbaert, A., Braimoh, A., Ndambi, A., Ayantunde, A., et al. (2025). "The Multifunctional Role of Livestock in East African Food Systems: the Case for Dairy," in *Pathways to African Food Security* (Milton Park: Routledge), 232-242 doi: 10.4324/9781032649696-24

Owen, G., (2020). What makes climate change adaptation effective? A systematic review of the literature. *Glob. Envir. Change* 62:102071. doi: 10.1016/j.gloenvcha.2020.102071

Paul, B. K., Butterbach-Bahl, K., Notenbaert, A., Nduah Nderi, A., and Ericksen, P., (2020). Sustainable livestock development in low- and middle-income countries: shedding light on evidence-based solutions. *Environ. Res. Lett*. 16:011001. doi: 10.1088/1748-9326/abc278

R Core Team. (2025) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Available online at: https://www.r-project.org/

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., et al. (2009). A safe operating space for humanity. *Nature* 461, 472–475. doi: 10.1038/461472a

Scholtz, M. M., Jordaan, F. J., Chabalala, N. T., Pyoos, G. M., Mamabolo, M. J., Neser, F. W., et al. (2023). A balanced perspective on the contribution of extensive ruminant production to greenhouse gas emissions in southern Africa. *Afr. J. Range Forage Sci*. 40, 107–113. doi: 10.2989/10220119.2022.2155247

Snapp, S., Kebede, Y., Wollenberg, E., Dittmer, K. M., Brickman, S., Egler, C., et al. (2021). *Agroecology and Climate Change Rapid Evidence Review: Performance of Agroecological Approaches in Low- and Middle- Income Countries (Research Report)* (CGIAR), 62.

Tamburini, G., Bommarco, R., Wanger, T. C., Kremen, C., van der Heijden, M. G. A., Liebman, M., et al. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci. Adv*. 6:eaba1715. doi: 10.1126/sciadv.aba1715

Tanner, J., Harris, P., Doubleday, H., Lekasi, J., and Kimani, S. (2000). *Manure Management in the Kenya Highlands: Collection Strategies to Enhance Fertiliser Quality and Quantity, 2nd Edn*. Ryton-on-Dunsmore: HDRA.

Tubiello, F. N., Salvatore, M., Cóndor Golec, R. D., Ferrara, A., Rossi, S., Biancalani, R., et al. (2014) *Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks*. Rome: Food and Agriculture Organization of the United Nations (FAO).

Udo, H., Weiler, V., Modupeore, O., Viets, T., and Oosting, S. (2016). Intensification to reduce the carbon footprint of smallholder milk production: fact or fiction? *Outlook Agric*. 45, 33–38. doi: 10.5367/oa.2016.0229

UNFCCC (2015). *United Nations Framework Convention on Climate Change*. Paris Agreement. Available online at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Wezel, A., Herren, B. G., Kerr, R. B., Barrios, E., Gonçalves, A. L. R., and Sinclair, F. (2020). Agroecological principles and elements and their implications for transitioning to sustainable food systems. *A review. Agron. Sustain. Dev*. 40:40. doi: 10.1007/s13593-020-00646-z

Zhu, Y., Butterbach-Bahl, K., Merbold, L., Oduor, C. O., Gakige, J. K., Mwangi, P., et al. (2024). Greenhouse gas emissions from sheep excreta deposited onto tropical pastures in Kenya. *Agric. Ecosyst. Environ*. 359:108724. doi: 10.1016/j.agee.2023.108724 644

Zhu, Y., Merbold, L., Pelster, D., Diaz-Pines, E., Wanyama, G.N., Butterbach-Bahl, K. (2018). Effect 645 of dung quantity and quality on greenhouse gas fluxes from tropical pastures in Kenya. 646 *Glob. Biogeochem. Cycles* 32, 1589–1604. doi: 10.1029/2018GB005949 359(84):108724