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EDITED BY
Aqeel Ahmad,
University of Florida, United States

REVIEWED BY
Calogero Schillaci,
Joint Research Centre, Italy
Ogechukwu Igboke,
North Dakota State University College of Arts and Sciences, United States

*CORRESPONDENCE
Monica Auteri
monica.auteri@unipa.it

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Life cycle assessment of Mediterranean hay production under variable climatic conditions: a case study

Simona Prestigiacomo[1], Monica Auteri[1*], Marzia Traverso[2], Rose Nangah Mankaa[2] and Giuseppe Di Miceli[1]

[1]Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze, Palermo, PA, Italy, [2]Institute of Sustainability in Civil Engineering, Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University, Aachen, Germany

Hay production represents a strategic component of Mediterranean forage systems, particularly in regions increasingly exposed to climatic variability. Despite its relevance for livestock-based economies, dedicated life cycle assessment (LCA) studies on hay production in semi-arid environments remain limited, and the influence of interannual climatic fluctuations on environmental performance is poorly documented. For this reason, the aim of the study was to apply LCA methodology to evaluate the environmental impacts associated with the production of mixed hay cultivated on a farm located in Cammarata (Agrigento, Italy) across three contrasting seasons (2021–2022, 2023–2024 and 2024–2025). These periods were characterized by substantial differences in rainfall distribution and yield. Two functional units (1 ton of hay; and 1 ha of cultivated land) and two life cycle impact assessment methods (CML-IA baseline and ReCiPe 2016 Midpoint/Endpoint) were adopted to improve robustness and comparability of results across different characterization models. Primary data were collected through field surveys, while secondary data were sourced from Ecoinvent database. Weighting and sensitivity analyses were used to support result interpretation. Results indicated that the driest season (S2) exhibited the lowest impacts per hectare but the highest impacts per ton of productivity. Under a mass-based functional unit, S2 recorded global warming potential values up to four times higher than the other seasons (S1 and S3), while under a land-based functional unit it consistently emerged as the lowest environmental impacts and the most favorable area-based profile. Across both the CML and ReCiPe methods, fuel consumption dominated impacts such as abiotic depletion, fossil depletion, and global warming potential, whereas fertilizers and on-field emissions were the main contributors to acidification, eutrophication, and marine ecotoxicity. Endpoint analysis indicated human health as the most impacted area of protection. Overall, the study demonstrates that climatic constraints strongly modulate environmental burdens in hay production. These findings highlight the importance of integrating climate variability into life cycle assessment and the need for integrated strategies that enhance mechanization efficiency, improve nutrient management, and adopt innovative technologies to increase resilience under increasing climatic stress.

KEYWORDS
climate variability, hay production, life cycle assessment (LCA), Mediterranean forage systems, yield

1 Introduction

Forage systems represent a key component of global agriculture, particularly in livestock production systems that rely on ruminant husbandry. In the European Union, forage crop production accounts for more than one third of the utilized agricultural area (UAA) (Eurostat, 2024). In countries such as Italy, forage crops constitute the dietary foundation of livestock systems and play a central role in food security, environmental sustainability, and land management. In addition, forage crops cover approximately 5.4 million hectares in Italy, corresponding to about 44% of the national UAA (Istat, 2025). Among the Italian regions, Sicily, the biggest island located at the heart of the Mediterranean basin, boasts a rich pastoral tradition deeply embedded in its history and culture. In terms of land use, permanent grasslands and forage crops occupy a significant portion of Sicily's agricultural land, consisting of about 53% of a total UAA of 1.279.707 ha (Istat, 2025). This extensive reliance on forage-based systems highlights the regional link between livestock production and the availability of forage throughout the year. In this context, forage systems, which largely rely on rainfed conditions, are increasingly threatened by ongoing climatic conditions (Soares et al., 2022). According to the Köppen–Geiger classification, Sicily falls within the temperate–humid (C-type) zone, with mean temperatures of the coldest month ranging between −3 and 18 °C (Kottek et al., 2006). Despite this temperate classification, the island exhibits high climatic vulnerability, qualifying as a climate hotspot within the Mediterranean basin (Lazoglou et al., 2024). Historical records indicate a long-term decline in annual precipitation, with Sicily losing approximately 150 mm over the period 1921–2003 (Basile and Panebianco, 2010). Recent analyses (2013–2023) reveal a significant reorganization of the seasonal cycle: summer and autumn precipitation increased, often in the form of extreme events, while winter and spring rainfall decreased (Pecorino et al., 2024). Concerning the temperature, between 1924 and 2003, Sicily warmed by approximately +1.38 °C (Basile and Panebianco, 2010). The past few years illustrate accelerated warming and increased climatic extremes: 2021 was marked by record-high temperatures and irregular rainfall, including extreme autumn events, while 2022 exhibited consistently positive temperature anomalies across all seasons (SNPA, 2023, SNPA, 2024). During 2023, Sicily experienced its driest semester since 1921, with up to 165 consecutive dry days and a regional temperature anomaly of +0.97 °C, followed in 2024 by a mean annual temperature +1.39 °C above the 1991–2020 climatological average (SNPA, 2024). These climatic constraints have exacerbated water scarcity, affecting crop yields and, consequently, increasing the environmental burden per unit of product (Knapp et al., 2002; Asseng et al., 2015; Rezaei et al., 2023). The dynamic relationship between agricultural practices and the environment is one marked by feedback loops, where environmental factors influence farming outcomes, and agricultural activities contribute to environmental changes. Within this context, understanding how varying production conditions, such as high and low yield seasons affect the environmental sustainability of agricultural practices is of critical importance. Different levels of crop productivity, often driven by climatic conditions, farming techniques, and external inputs, can lead to significantly different environmental outcomes, necessitating a thorough evaluation to understand the trade-offs involved. Hay production systems provide a wide range of ecosystem services that extend well beyond their primary role of supplying feed. They are essential for generating farm income, maintaining agrobiodiversity, preserving rural landscapes, supporting soil fertility and carbon storage, and ultimately contributing to nutritional quality and food security (Lüscher et al., 2014; Schils et al., 2022). Despite the strategic importance of hay production in ruminant systems, there is still a lack of dedicated Life Cycle Assessment (LCA) studies, particularly in Mediterranean regions such as Italy. A list of studies focused on forage production is reported in Supplementary Table 1. Most of these studies focused on forage or forage-derived products, in contexts that differ from Italian system, both within and outside the European Union. Regarding the Italian context, only one study (Bacenetti et al., 2018) was specifically focused on detailed LCA of alfalfa hay production in Northern Italy. The work provided valuable insights into input flows and output emissions for different management scenarios (irrigated vs. non-irrigated, conventional vs. organic), within the specific context of the Po Valley. However, the geographical, pedoclimatic, and agronomic framework of that study differs substantially from that of Mediterranean and semi-arid environments such as Sicily. Importantly, these studies generally assume stable climatic conditions or average or historical climate data, neglecting the effects of interannual variability, seasonal extremes, and climate change on forage yields and associated environmental impacts. An LCA tailored to hay production in Sicily would provide a comprehensive evaluation of the environmental burdens associated with local cultivation practices. This localized assessment could be useful for identifying hotspots where interventions can optimize resource efficiency and reduce ecological footprints, thus promoting more sustainable forage production systems in a region vulnerable to climate change. Furthermore, Sicily's reliance on livestock farming, particularly small ruminants, underscores the need for sustainable forage supply chains that support both economic viability and environmental conservation. For all these reasons, the aim of the study was to apply LCA methodology to evaluate the environmental impacts associated with the production of mixed hay cultivated on a farm located in Cammarata (Agrigento, Italy). The present Sicilian case study explicitly considers climate induced variations in rainfall, temperature, and drought frequency, providing a more realistic assessment of the environmental impacts per unit of hay produced under Mediterranean conditions.

2 Materials and methods

The growing focus on environmental sustainability has led to the adoption of methodologies such as LCA to evaluate the impacts of various production systems (Brentrup et al., 2004). This method is regulated by the International Organization for Standardization (ISO), (ISO 14074:2022, ISO 14040:2006 + A1:2020, ISO 14044:2006 + A2:2020) (ISO, 2022, 2006a, b). LCA consists of four different steps: Goal and Scope definition; Inventory Analysis

(LCI); Impact Assessment (LCIA) and interpretation of results. The purpose and the objectives of all phases will be explained in the following paragraphs.

2.1 Goal and scope

The present study applied a multifunctional LCA to investigate the environmental performance of hay production systems, with the following objectives:

1. To compare three distinct growing seasons in hay production, taking into account the differences in terms of rain and temperatures that influenced yield;
2. To quantify the environmental impacts of the various production stages and identify the main contributors;
3. To analyze the differences between 2 functional units (FUs) and two methods.

This study is intended for hay producers, researchers, and policymakers seeking strategies to improve the sustainability of hay production systems. With this study, the authors aim to capture the complexity of hay production systems, to identify opportunities for mitigating environmental pressures.

2.1.1 System boundary and functional unit

A cradle to farm gate approach was applied. All the steps included in the system boundaries were specified in Figure 1.

They cover all background processes, such as the production of fertilizers, fuel and seeds, the cultivation process, the production of packaging materials and the delivery of hay to the storage center. Considerations for farm infrastructure, machinery production, changing in land use, human labor, and maintenance were not taken into account. The assumptions included that all products were transported by 3.5 - 7.5 lorry EURO 4 and the distance considered was between the site of production and the storage center. In LCA studies, defining a FU is crucial to account for the impact of a product; it represents a measurable reference that quantifies the performance of the product system (according to ISO 14040:2006, 14044:2006) (ISO 2006a, b). In agricultural context, and particularly about forage systems, they are widely used three types of FU:

a. Mass-based, such as the mass of 1 ton of dry matter forage (Fathollahi et al., 2018; Ghaderpour et al., 2018; Bacenetti et al., 2018; Lehtilä et al., 2024; Bai et al., 2025), 1 bale of hay (Stylianou et al., 2023).
b. Area-based, such as 1 ha of cultivated land (González-García et al., 2016; Xu et al., 2022).
c. Energy-based, such as 1 MJ of forage yield (Lehtilä et al., 2024) or 1 MJ metabolizable energy (González-García et al., 2016).

To more accurately capture the characteristics of the investigated system, multiple FU options were considered. In particular, two distinct FUs were adopted: one based on the amount of product (1 ton of hay), the other on the cultivated area (one hectare of land). The choice of these two FUs is intended to capture the inherent trade-off in agricultural LCA: while area-based indicators reflect the intensity of cultivation and local pressure on the land, mass-based indicators highlight the environmental efficiency of the system relative to its productivity.

2.1.2 Databases and data quality

The LCA will be performed using the SimaPro software (version 9.5.0.2), developed by PRé Consultants, in accordance with the ISO 14040 and ISO 14044 standards (ISO 2006a, b). The data will be primarily collected through structured field surveys, conducted over three distinct agricultural seasons hereafter referred to as: S1 (2021–2022, standard rainfall and intermediate yield), S2 (2023–2024, extreme drought and low yield), and S3 (2024–2025, high-yield season characterized by abundant rainfall). The 2022–2023 agricultural season was excluded from the analysis due to crop rotation management, as the field under investigation was temporarily assigned to another use and hay was not cultivated. When primary data will not be available, background information will be

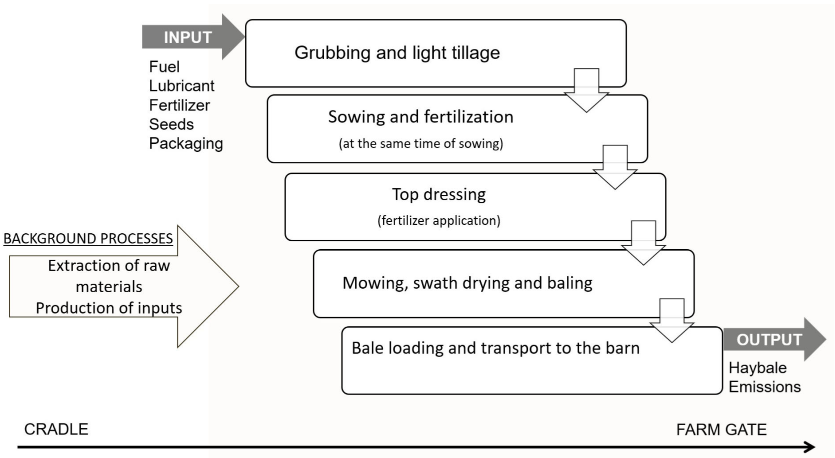

FIGURE 1
System boundaries considered in this study.

supplemented using secondary data sourced from the Ecoinvent database (version 3.0), particularly for processes related to raw material extraction, seed production, and the manufacturing of agricultural inputs such as fertilizers, fuels, and lubricants.

2.1.3 LCIA methodology and impact categories

In the contest of goal and scope, this section outlines the methodological framework that will be adopted for the LCIA and the selection of impact categories considered in the study. Environmental impacts will be assessed through the application of two internationally recognized methods, to ensure robustness and comparability of results: the CML-IA baseline (version 3.09, EU25) and ReCiPe 2016 (v1.08), applying the Hierarchist perspective (World 2010 H) at both midpoint and endpoint levels. The differences between the two methods are indicated in Supplementary Table 2. CML is a well-established midpoint-oriented methodology commonly applied in the environmental assessment of arable crop systems (Bruijn et al., 2004). The version that will be adopted (3.09, EU25) reflects average European conditions and is commonly recommended for studies focused on European production systems. The method includes eleven midpoint impact categories: Abiotic Depletion Potential (AD), Abiotic Depletion of fossil fuels (ADff), Acidification Potential (AP), Eutrophication Potential (EP), Freshwater Aquatic Ecotoxicity (FE), Global Warming Potential (GWP), Human Toxicity Potential (HT), Marine Aquatic Ecotoxicity (ME), Ozone Layer Depletion (OLD), Photochemical Oxidation (PO), and Terrestrial Ecotoxicity Potential (TE). To enhance interpretability, results from the CML-IA method will be normalized. The ReCiPe 2016 represents a more recent and comprehensive LCIA method, offering both midpoint and endpoint indicators (Huijbregts et al., 2017). The midpoint method includes a total of 18 impact categories: Global warming (GWP), Stratospheric ozone depletion (ODP), Ionizing radiation (IR), Ozone formation, Human health (OF-HH), Fine particulate matter formation (PMF), Ozone formation, Terrestrial ecosystems (OF-TE), Terrestrial acidification (TA), Freshwater eutrophication (FEU), Marine eutrophication (MEU), Terrestrial ecotoxicity (TET), Freshwater ecotoxicity (FET), Marine ecotoxicity (MET), Human carcinogenic toxicity (HTc), Human non-carcinogenic toxicity (HTnc), Land use (LU), Mineral resource scarcity (MRS), Fossil resource scarcity (FRS), Water consumption (WC). To simplify the analysis, the results of the characterization will be shown for only six categories (GWP, FET, MET, LU, HTnc and HTc). The ReCiPe 2016 endpoint method provides a clearer and more accessible view of environmental impacts by grouping results into three main areas: human health, ecosystem quality, and resource availability. This makes it easier to understand the broader consequences of agricultural practices and supports more informed decision-making. In the case of the ReCiPe 2016 endpoint, only weighting will be shown. Moreover, to ensure the quality of the analysis, a sensitivity analysis of transport will be performed considering the ±5% of the impact of this input through CML method.

2.2 Life cycle inventory

Primary data on yield, agricultural practices, farming inputs and output were collected from a single farm located in the municipality of Cammarata, in the province of Agrigento, Sicily, Italy. The farm is located on hilly terrain and it covers a total area of 9 hectares, of which 4.5 hectares are dedicated to hay production with rainfed irrigation. The area is characterized by semi-arid climate (Regione Siciliana, 2026) and regosoil on clay rocks (Ballatore and Fierotti, 1967). Over the three-year period, the products considered were mixed hay (<15% moisture content) from three different annual species, indicated in Table 1. Different fertilization strategies were adopted to cope with variable climatic conditions. All information concerning the farm is available in Table 1. The farm follows a livestock-based production system. A structured questionnaire was developed to ensure consistency and completeness in data collection, and information was gathered through direct interviews with the technical staff of the farm. Data collected were referred to the three growing seasons mentioned above, each extending from September (sowing) to May (harvest). Temperature patterns of the site study remained relatively stable across the three growing seasons (Figure 2), with observed maximum temperatures (solid lines) that were consistently above historical averages (dashed lines), indicating that the effects of climate warming were evenly distributed over time. Concerning the rainfall pattern (Figure 3), the seasons were differently affected by climate change dynamics, resulting in irregular rainfall patterns. Although the total rainfall amount in S1 was comparable to that of S3, its distribution was uneven, with most precipitation occurring early in the season. In contrast, S2 experienced scarce rainfall throughout the growing period, which severely limited forage growth. S3, on the other hand, was characterized by abundant rainfall between January and February, leading to the highest yield compared with S1 and the much driest S2 (Table 1). Details about LCI and background data are presented in Table 2 and S3.

The direct and indirect emissions of nitrogen (N) to air and water were estimated following the methodological approach outlined in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019). Similarly, phosphorus (P) emissions to environmental compartments were assessed using the methodology proposed by Zampori et al. (2019). To simplify, these emissions were indicated in the results section as "on field

TABLE 1 Information about location, yield, species and fertilizers adopted during the three seasons in the farm.

Season	Yield (t ha^{-1})	Location (m a.s.l.)	Municipality	Species	Fertilization type	Fertilization formula
S1	6.25	400	Cammarata (AG) Italy	*Trifolium squarrosum; Lolium multiflorum; Avena sativa*	Mineral	P_2O_5; Urea (46% N)
S2	1.5					P_2O_5
S3	8.5					P_2O_5; Urea (46% N)

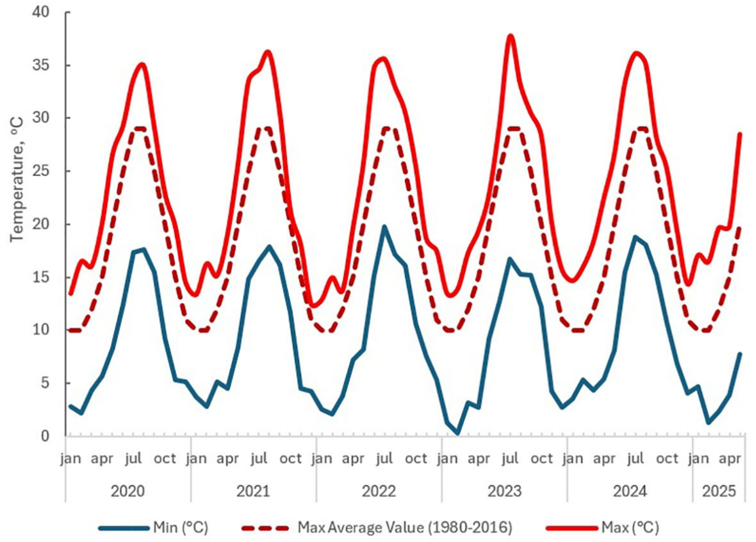

FIGURE 2
Temperature patterns from 2020 to 2025 at the study site in Cammarata (Agrigento, Italy), compared with the long-term maximum temperature mean recorded for the reference period 1980–2016.

emissions". The inventory of heavy metals was calculated following SALCA method. The input categories and background data are listed in Table 2 and S3, and they were grouped according to common features found in the results leading to these categories:

- Fertilizers: This includes the production of all fertilizers made with nitrogen (N) and phosphorus (P).
- Fuel: Covers both the production of fuel and the emissions from farming activities.
- Lubricants: Refers to the production of oils used in agricultural machinery.
- Packaging: Involves production of materials used to package fertilizers, seeds and the wrapping used for hay bales.
- Seeds: Relates to the production of seeds.
- Transport: Covers the movement of inputs from the site of production to the farm. Additionally, it covers the transport of haybale to the barn.

3 Results

3.1 CML methodology and recipe midpoint characterization

An analysis of the raw CML and ReCiPe characterized results, indicated that none of the impact categories showed differences of more than one order of magnitude. However, the results of the LCA analysis revealed distinct variations in environmental impacts, reflecting differences in management intensity, input use, and crop yield. The radar chart (Figures 4, 5) provides a comparative visualization of the environmental impact profiles using a min-max normalization approach. In this method, each impact value is expressed as a fraction of the maximum value observed within its respective category, effectively scaling the highest value in each category to 1.0 and the others proportionally. A lower normalized value indicates better environmental performance in that specific

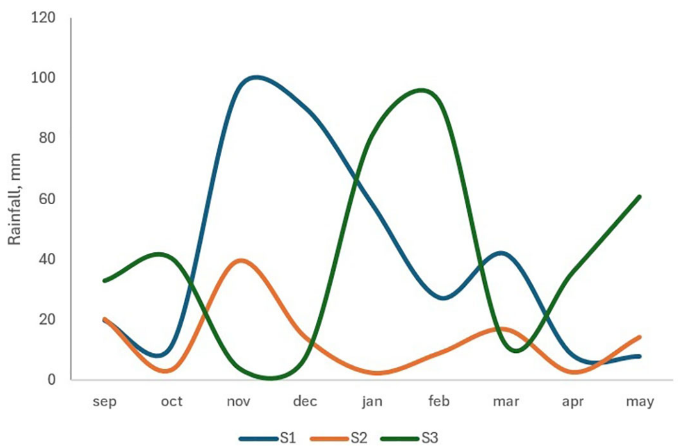

FIGURE 3
Season rainfall distribution from September to May for S1, S2, S3 in the site study in Cammarata (AG).

TABLE 2 **Life cycle inventory with data described over the three growing seasons and for two FUs (per ton and per ha).**

Items	FU/ha			FU/ton		
	S1	S2	S3	S1	S2	S3
Fuel (l)	1.34E+02	1.24E+02	1.34E+02	2.14E+01	8.27E+01	1.58E+01
Lubricant (kg)	4.30E-01	3.80E-01	4.07E-01	6.88E-02	2.53E-01	4.79E-02
Seeds (kg)	5.50E+01	5.50E+01	5.50E+01	8.80E+00	3.67E+01	6.47E+00
Packaging (kg)	3.30E+00	1.35E+00	4.60E+00	5.28E-01	8.99E-01	5.41E-01
Transport (kgkm)	2.11E+05	1.30E+05	3.28E+05	3.37E+04	8.64E+04	3.85E+04
P_2O_5 fertilizer (kg)	3.71E+01	3.71E+01	3.71E+01	5.94E+00	2.47E+01	4.37E+00
N Fertilizer (kg)	2.76E+01	0.00E+00	6.90E+01	4.42E+00	0.00E+00	8.12E+00

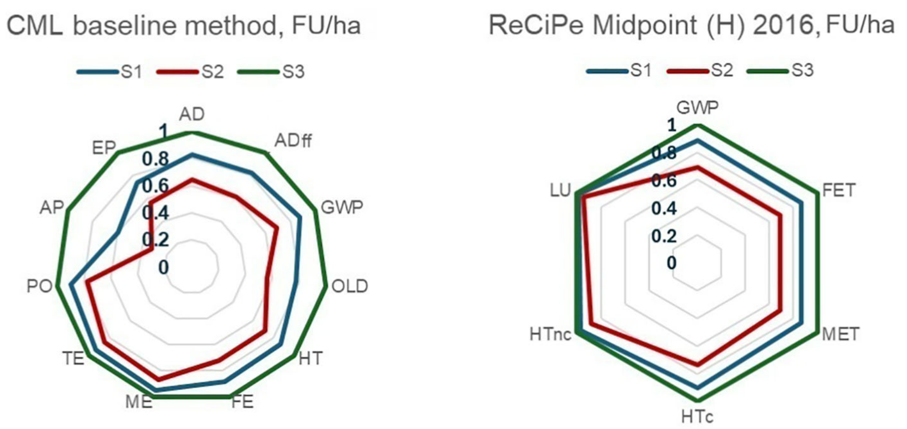

FIGURE 4
Normalized results of CML baseline method per hectare (left) and ReCiPe midpoint method per hectare (right). The data are normalized (0–1 scale) for the three productive seasons (S1, S2, S3). The value was obtained by dividing each category value by the maximum observed across the seasons. legend for CML baseline method: AD, abiotic depletion potential; ADff, abiotic depletion of fossil fuels; GWP, global warming potential; OLD, ozone layer depletion; HT, human toxicity potential; FE, freshwater aquatic ecotoxicity potential; ME, marine aquatic ecotoxicity potential; TE, terrestrial ecotoxicity potential; PO, photochemical oxidation; AP, acidification potential; EP, eutrophication potential. legend for ReCiPe midpoint method: GWP, global warming; FET, Freshwater ecotoxicity; MET, marine ecotoxicity; HTc, human carcinogenic toxicity; HTnc, human non-carcinogenic toxicity; LU, land use.

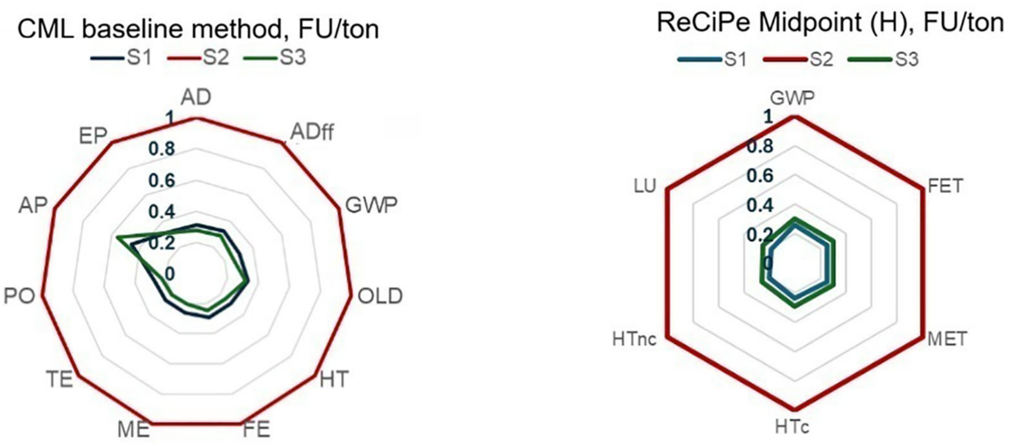

FIGURE 5
Results from CML baseline method per ton (right) and ReCiPe midpoint method per ton (right). The data are normalized (0–1 scale) for the three productive seasons (S1, S2, S3). The value was obtained by dividing each category value by the maximum observed across the seasons. CML baseline method: AD, abiotic depletion potential; ADff, abiotic depletion of fossil fuels; GWP, global warming potential; OLD, ozone layer depletion; HT, human toxicity potential; FE, freshwater aquatic ecotoxicity potential; ME, marine aquatic ecotoxicity potential; TE, terrestrial ecotoxicity potential; PO, photochemical oxidation; AP, acidification potential; EP, eutrophication potential. ReCiPe midpoint method: GWP, global warming; FET, freshwater ecotoxicity; MET, marine ecotoxicity; HTc, human carcinogenic toxicity; HTnc, human non-carcinogenic toxicity; LU, land use.

impact category. When expressed per hectare (Figure 4), the S2 season showed the lowest environmental impacts across all categories analyzed. In contrast, the S3 season consistently recorded the highest impacts per hectare suggesting increased input intensity and lower system efficiency. Concerning the CML Method (Figure 4), the radar chart showed that ME, TE and PO exhibited highly similar normalized values across the scenarios, suggesting comparable emissions or pressure on these compartments regardless of the management strategy. In contrast AD, ADff, GWP and OLD displayed more marked differences between scenarios. The most divergent category, however, was AP where scenario S3 reached a peak far above the others. In contrast, S2 outlined the smallest polygon on the radar chart, with values located closer to the center. S2 scored the lowest in key indicators such as acidification (AP = 0.31) and eutrophication potential (EP = 0.56). Using the ReCiPe 2016 Midpoint indicators (Figure 4), S2 showed the lowest impact across most categories when results were expressed per hectare, particularly in the categories GWP, FET and MET where the impact was only 69% compared to S3. It also showed a marked improvement in HTc, with impacts reduced to 74% compared with S3. Although S2 overall S3 across all categories, the improvements were less pronounced for LU and HTnc, where the impacts corresponded to 95% and 88% of those in S3, respectively. On the other hand, S1 was almost identical to S3 in terms of LU (99%) and HTnc (97%), indicating negligible improvement in these categories. This scenario provided moderate reductions (ranging from 10% to 13%) in GWP, FET, MET, and HTc, with relative impacts between 87% and 90%. However, the interpretation shifts when results are expressed per unit of product (FU/ton).

Concerning the CML Method (Figure 5), S2, despite its favorable per-hectare profile, exhibited the highest impact values per ton ranging from 3.1 to 4.9 times higher than those of S1 and S3. In terms of GWP, S2 emitted approximately 512 kg CO_2 eq which is nearly four times higher than S1 (130 kg CO_2 eq) and over three times higher than S3 (155 kg CO_2 eq). S3 outperformed S1 across all four toxicity indicators (HT, FE, ME and TE). A notable exception emerged in the AP category, where S1 (45%) performed better than S3 (55%). The environmental impacts per ton of hay produced, using Recipe 2016, as shown in Figure 5, revealed marked differences across the three seasons. S1 clearly represented the most preferable option from an environmental standpoint, showing a drastic improvement compared with S2, with impacts reduced to only 19–26%. The greatest benefit was observed in LU, where S1 accounted for only 19% of the impact of S2, corresponding to an 81% reduction. GWP exhibits only 26% of the impact of S2, representing a 74% reduction. Scenario S3 also shows a substantial improvement compared with S2.

3.2 Hotspot analysis

To identify the key issues, a contribution analysis was carried out. The contribution analysis revealed that the environmental impact profile was dominated by three primary hotspots: fuel, on-field emissions, and fertilizer across both functional units assessed (per hectare and per ton). Concerning the CML/ton (Figure 6), across the three seasons, fuel consistently emerged as the dominant contributor to the majority of impact categories, particularly for AD and ADff, GWP and HT. Its contribution ranged between 50% and 77%. Fertilizers represented the second most relevant hotspot in several categories, notably OLD, ME, and GWP, where their contribution reached up to 44% in S3. In contrast, on-field emissions were negligible in most categories but dominated those directly related to nitrogen losses AP and EP. In these categories, contributions ranged from 43% to 85%, particularly pronounced in S3.

Concerning the CML FU/ha (Supplementary Figure 1), fuel was primarily associated with mechanized field operations and it was the dominant contributor to environmental impacts in multiple categories. Its contribution was particularly high in seasons S1 and

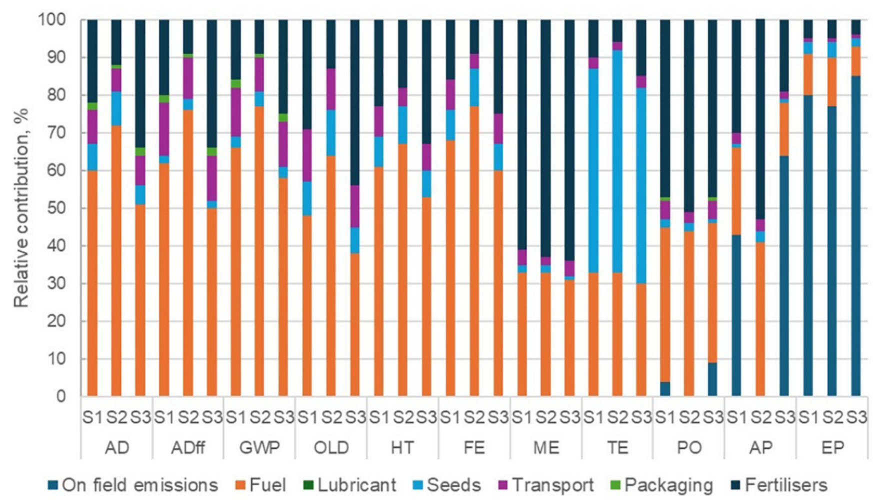

FIGURE 6
Values of relative contributions (%) for the three seasons regarding all factors involved in the process, for a ton of hay with CML baseline method. AD, abiotic depletion potential; ADff, abiotic depletion of fossil fuels; GWP, global warming potential; OLD, ozone layer depletion; HT, human toxicity potential; FE, freshwater aquatic ecotoxicity potential; ME, marine aquatic ecotoxicity potential; TE, terrestrial ecotoxicity potential; PO, photochemical oxidation; AP, acidification potential; EP, eutrophication potential.

S2, where it consistently accounted for over 60% and up to 80% of the total impact on indicators such as AD, ADff, GWP, HT and FE. On-field emissions showed variable but substantial contributions in specific impact categories. It was the dominant hotspot for EP often representing nearly 80% of the impact in this category across all seasons. Regarding AP, on-field emissions were the main contributors in S1 and S3, representing approximately 45% and over 60% of the total impact, respectively. Conversely, in S2, fertilizers were identified as the main contributors to AP for both functional units. This can be attributed to a comparatively higher application rate and to fertilizer composition, which likely enhanced ammonia and nitrogen oxide emissions during that season. Fertilizers played a major role in categories sensitive to nutrient use, such as ME and PO. Their relative contribution was highest in season S3, exceeding 60% in AP and reaching about 44% in OLD, suggesting more intensive nutrient application. Minor contributors included seeds, which were only relevant in specific toxicity-related categories of TE contributing up to 50–60% of the impact. Transport, lubricants and packaging were negligible. The ReCiPe Midpoint results per hectare (Supplementary Figure 2) confirm fuel as the dominant hotspot across most impact categories (65–80%), consistent with CML findings. Its contribution slightly decreases in S3, where fertilizers become more relevant (up to 28%), especially in GWP, FET, and MET. Seed production showed a notable contribution (20–26%) in HTnc. In contrast, LU was mainly associated with seeds (approx. 60%) and, to a lesser extent, fuel and fertilizers. The ReCiPe Midpoint 2016 results per ton confirmed the predominance of fuel consumption, with fertilizers and seeds showing a trend similar to that observed per hectare (Supplementary Figure 3).

3.3 ReCiPe endpoint weighing and sensitivity analysis

Endpoint weighted values were calculated using the ReCiPe method and expresses them in points (Pt). Human health was found to be the most affected for both investigated systems, followed by Ecosystems and Resources. The last one contributed minimally to the total score for both systems. The choice of FU influenced results. Per hectare (Supplementary Figure 4), S2 showed the highest overall impacts, whereas per ton of product (Figure 7), S3 was the most impactful. Differences between systems were more pronounced per hectare. The results and comments of sensitivity analysis were reported in Supplementary Materials (Supplementary Table 4).

4 Discussions

The results of the study revealed consistent patterns that enhance understanding of system sustainability aiming to improve nutrient use efficiency under drought conditions. Although the analysis of the raw CML and ReCiPe characterized data indicated that none of the impact categories exhibited differences greater than one order of magnitude, it was nonetheless evident that climatic conditions exerted a certain influence on these outcomes. The combination of rainfall scarcity and elevated temperatures significantly restricted plant growth and yield, particularly under rainfed management as indicated by Staniak and Kocoń (2015). In particular, they found that drought events combined with high temperatures may reduce forage grass yields by approximately 30% in Poland. In this current case study, the reduction of hay yield during S2 reached 76% and 82% in comparison to S1 and S3, respectively, suggesting that the impact of climatic stress strongly influenced the forage productivity under Mediterranean conditions such as those in Sicily, especially for rainfed crops. A clear trend emerged showing that S2 generally exhibited the lower environmental burdens when impacts were considered per hectare. This reduction suggests that during S2, the management approach was oriented toward minimizing spatial pressure and nutrient runoff, which is corroborated by both CML and ReCiPe midpoint indicators. Conversely, S2 consistently showed the highest impact value when FU was expressed per ton, mainly due to its substantially lower yield compared to S1 and S3. This inverse relationship reflects that reductions in input intensity per unit area generally decrease total

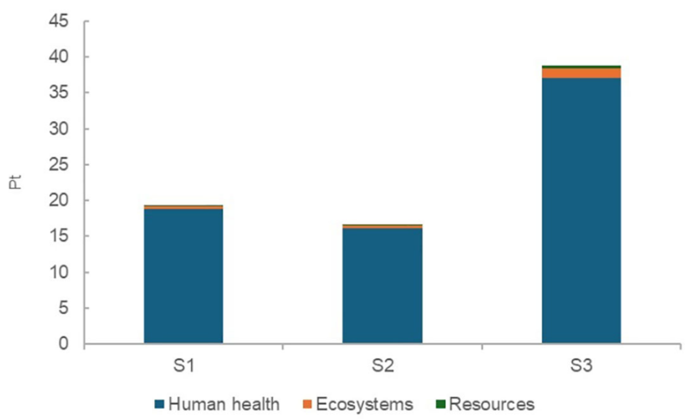

FIGURE 7
Results of ReCipe endpoint weighted per ton of hay.

environmental pressures per hectare but may also reduce yield. As a consequence, the same environmental burdens are distributed over a smaller amount of products, leading to higher impact values per ton of output (Pérez et al., 2024; David et al., 2025). Therefore, considering only a mass-based FU does not provide a balanced view of the impacts. To overcome this limitation, it is always recommended to use both mass-based and area-based functional units in LCA assessment of agriculture (González-García et al., 2016; Salou et al., 2017), as they describe complementary aspects of sustainability: spatial efficiency versus productivity efficiency. Consequently, the investigated seasons should not be interpreted through an absolute sustainability ranking, but rather through perspective-dependent environmental trade-offs. Regarding the analysis of impact categories, they were similar for both FUs. On an area basis, the greatest variation was observed for AP, largely due to differences in fertilizer amount and use across seasons. Conversely, LU demonstrated very low differences due the fact that the intensity of the soil use was almost the same over all seasons. However, as expected, per-ton results showed much wider differences, confirming the dominant influence of yield variations on overall impact intensity. The magnitude of our results was generally in accordance with the data reported by Fathollahi et al. (2018) per ton of product of corn silage and alfalfa hay. The values for AD, ADff, GWP, ME, PO, AP, TE, and EP fall within the same order of magnitude. Slight variations were observed for AD in S3, for ME in S2 and for TE in S1 and S3. For OLD, HT and FE, the difference is bigger than the other categories, reached also one to four orders of magnitude. Agricultural mechanization is responsible for a significant amount of impacts, primarily due to fuel consumption (Bacenetti et al., 2018). Indeed, as shown by the analysis of environmental hotspots for both methods, fuel mostly affected AD, ADff, GWP, OLD, HT, FE, and ME under CML, and to GWP, HTc, and HTnc under ReCiPe. Similarly, Bai et al. (2025) indicated fuel and fertilizers production as major concerns to produce alfalfa. Moreover, fuel was indicated as one of the main factors to ADff and OLD for barley production, as indicated by Payandeh et al. (2021). Conversely, the study of Parajuli et al. (2017) reported that one of the main contributors to GWP was agro-chemicals production. Notably, there was a difference between the two methods for both FUs in the category of marine aquatic ecotoxicity; in CML the major contributor was fertilizers manufacturing, while in ReCiPe it was fuel use. Indeed, choosing different methods could influence the results of the analysis, because of differences in characterization modelling and the substance coverage by individual impact categories (Rybaczewska-Błażejowska and Jezierski, 2024). Field emissions represented another critical hotspot, for AP in S1 and S3 and for EP for all seasons; regarding the last category this is aligned with results of Fathollahi et al. (2018) and Parajuli et al. (2017), who reported fertilizer-related emissions as the dominant contributors to these categories. Xu et al. (2022) demonstrated that, for AP, the major contributors were fertilizers, according to the results for S2. However, Nemecek et al. (2024) indicated that NH_3 emissions are important contributors to both acidification and eutrophication, which is consistent with the results of this study, where NH_3 emissions were included among on field emissions. Concerning sensitivity analysis, among the tested scenarios, S3 showed the highest response to parameter variation, particularly for GWP and ADff. This behavior suggests a greater dependence of this scenario on transport-related inputs, which increases the effect of small changes in operational patterns. Finally, endpoint weighting using ReCiPe 2016 indicated that human health was the most affected area of protection, primarily due to climate-change and fine-particulate-matter formation, in agreement with the results of Dekker et al. (2020) for food production systems.

5 Conclusions

Climatic variability, in particular the scarcity of precipitation, emerged as a key factor influencing the environmental performance of Sicilian hay production, with yield representing the main driver of impact intensity. High-yield seasons (S1, S3) tended to reduce impacts when FU expressed per ton of hay, but increased pressures per hectare, whereas drought years (S2) reversed this pattern, underlining the complex interplay between productivity and environmental burdens. Fuel use and fertilizers consistently dominated the main impact categories, whereas seeds, on-field emissions, and other inputs such as transport and packaging had comparatively minor effects. These results underscore the importance of explicitly accounting for interannual climatic variability in LCA studies, as it allows a more accurate understanding of how environmental impacts fluctuate with production conditions. By analyzing production, this study demonstrates the added value of season-specific assessments. Such an approach not only clarifies the role of climate in shaping environmental performance but also could support the identification of targeted strategies to enhance sustainability. In particular, improving mechanization efficiency, adopting precision agriculture techniques, optimizing nutrient management boosting funding for new fertilizers, such as biostimulants or nature based with a lower impact, could mitigate environmental pressures while maintaining or increasing yield, even under challenging climatic conditions. Over time, integrating these insights into predictive models could guide decision-making to balance productivity and environmental sustainability in Mediterranean forage systems. Overall, the findings highlight that sustainability in agriculture should be defined not merely as the reduction of environmental impact, but as the capacity of agroecosystems to adapt to climatic fluctuations, regenerate resources, and maintain productivity in a resilient manner. The LCA framework provides a robust methodology to quantify these dynamics and translate local practices into actionable indicators. For Mediterranean hay production, this study illustrates how integrating seasonal variability, climate-adaptive management, and innovative practices can create resilient systems that reconcile productivity goals with environmental protection, offering a model for sustainable forage production under the pressures of ongoing climate change.

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

SP: Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. MA: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. MT: Conceptualization, Resources, Supervision, Validation, Writing – review & editing. RM: Software, Supervision, Validation, Writing – review & editing. GM: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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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.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2026.1804940/full#supplementary-material

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