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Climate change and socio-economic assessment of PLF in dairy farms: Three case studies

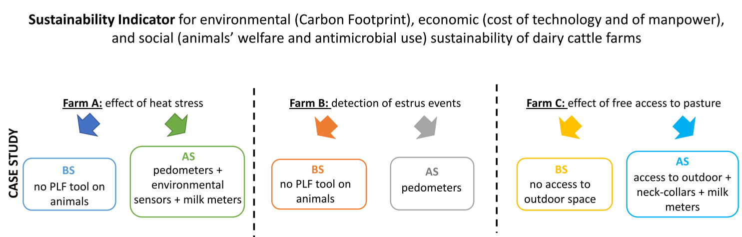
Daniela Lovarelli [a,*], Lorenzo Leso [b], Marco Bonfanti [c], Simona Maria Carmela Porto [c], Matteo Barbari [b], Marcella Guarino [a]

[a] Department of Environmental Science and Policy, via Celoria 2, 20133, Università degli Studi di Milano, Italy
[b] Department of Agricultural, Food, Environmental and Forestry Sciences and Technologies, Via San Bonaventura 13, 50145, Università degli Studi di Firenze, Italy
[c] Department of Agriculture, Food and Environment, via Santa Sofia 100, 95123, Università degli Studi di Catania, Italy

HIGHLIGHTS

- Environmental and socio-economic sustainability pillars were used for an indicator.
- Climate change, animal welfare, antibiotic use, manpower and technology were criteria.
- Three dairy farms were tested with baseline (traditional) vs alternative (PLF-based).
- All PLF-based scenarios resulted a better sustainability indicator than baseline.

GRAPHICAL ABSTRACT



RESULTS

Sustainability indicator	Farm A		Farm B		Farm C	
	BS	AS	BS	AS	BS	AS
Sustainability score	16	25	15	21	16	22
Improvement (%)		+56%		+40%		+38%

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ABSTRACT

Precision Livestock Farming (PLF) techniques include sensors and tools to install on livestock farms and/or animals to monitor them and support the decision making process of farmers, finally early detecting alerting conditions and improving the livestock efficiency. Direct consequences of this monitoring include enhanced animal welfare, health and productivity, improved farmer lifestyle, knowledge, and traceability of livestock products. The indirect consequences, instead, include improved Carbon Footprint and socio-economic indicators of livestock products.

In this context, the aim of this paper is to develop an indicator applicable to dairy cattle farming that takes into account concurrently these indirect consequences. The indicator was developed combining the three sustainability pillars (with specific criteria): environmental (carbon footprint), social (5 freedoms of animal welfare and antimicrobial use) and economic (cost of technology and manpower use). The indicator was then tested on 3 dairy cattle farms located in Italy, where a baseline traditional scenario (BS) was compared with an alternative scenario (AS) where PLF techniques and improved management solutions were adopted. The results highlighted that the carbon footprint reduced in all AS by 6–9 %, and the socio-economic indicators entailed improvements in animals and workers welfare with some differences based on the tested technique. Investing in PLF techniques determines positive effects on all/almost all the criteria adopted for the sustainability indicator, with case-specific aspects to consider. Being a user-friendly tool that supports the testing of different scenarios, this indicator could be used by stakeholders (policy makers and farmers in particular) to identify the best direction towards investments and incentive policies.

* Corresponding author.
E-mail address: daniela.lovarelli@unimi.it (D. Lovarelli).

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1. Introduction

In the European Union, the attention to agricultural and livestock aspects has been high for a long time and researchers and stakeholders are currently looking for solutions to enhance the sustainability of these productions (Thornton, 2010; Vanvanhossou et al., 2021; White et al., 2014). Agricultural and livestock productions are essential for human beings and bring a series of positive effects on the environment and on the socio-economic indicators (Pardo et al., 2022; Tullo et al., 2019). However, investments to enhance the efficiency and the potentialities of the sector are needed. In this context, the main drawback is that the sector is not much appealing for young people, and workers are diminishing constantly over the years. To head towards improved efficiency, sustainability, and generational renewal, technological investments are required. Policy incentives are present (e.g. European Common Agricultural Policy), however, redesigning the subsidies to allow farmers achieve an economic, environmental, and social sustainability could bring additional benefits to this production sector (Brown et al., 2021; Pe'er et al., 2020).

In the European Union, the recently-ended Common Agricultural Policy (CAP 2014–2022) started to encourage sustainable agricultural productions (Pardo et al., 2020) and the current one (CAP 2023–2030) is continuing towards this direction. Moreover, other recent European policies such as the From Farm to Fork Strategy within the framework of the European Green Deal and the National Recovery and Resilience Plan introduced in Italy (European Commission, 2020) will be fundamental to incentivize the efficiency improvements in the agricultural and livestock sectors. With these plans, policy makers expect to enhance the efficiency of the sectors, by improving productivity with a significant attention to the environment. In particular, attention to biodiversity, organic productions, a reduced use of pesticides and anti-microbial medicines are the key goals of these programs. To achieve them, however, farmers will need to invest in technology and thus encourage efficient and sustainable productions (Morrone et al., 2022). Without technology for agriculture (e.g., sensors and tools to monitor fields, prescription maps, etc.) (McBratney et al., 2005) and for livestock (e.g., sensors and tools to monitor animal behavior, barn environments, etc.) (Lora et al., 2020) achieving the European targets is almost impracticable because technology brings knowledge that otherwise would miss (Rojo-Gimeno et al., 2019).

In detail, precision agriculture and precision livestock allow to monitor in real time and even remotely the field and animal productions, health and welfare, to model and support the decision-making process of farmers (Berckmans, 2014; McBratney et al., 2005), finally avoiding undermining the desired efficiency efforts of European policies (Beckman et al., 2020; Eriksson et al., 2020). Focusing on the livestock sector, precision livestock is known as Precision Livestock Farming (PLF) and involves the installation of tools and sensors on the farm and/or on the animals (e.g., environmental sensors, behavioral sensors, milking sensors, cameras, microphones, etc.) to monitor continuously and in real-time the barn environments (temperature, humidity, air quality) and the animals (productivity, behavior, health, welfare) (Berckmans, 2014). Collecting such a big amount of detailed data, storage and processing expertise is needed, possibly following an IoT scheme (Riaboff et al., 2022). Data processing generally results in prediction models that early detect illnesses or health and welfare problems, or in increased knowledge adoptable by the farmer to improve the farm and animals management, finally achieving the required efficiency improvements in socio-economic and environmental terms (Chen and Holden, 2018; Hyland et al., 2022; Schillings et al., 2021). Indeed, the main direct aim of PLF is the monitoring of animals and their living conditions; however, PLF determines effects also on the use of resources, and thus on the socio-economic and environmental sustainability of livestock productions (targeted costs and targeted use of inputs) (Capper et al., 2009; Lovarelli et al., 2020; Perry et al., 2018; Van der Linden et al., 2020). In order to investigate if and how much the adoption of PLF and improved management practices can influence the sustainability improvements on dairy cattle farms to respond to the international policies, this study aims to develop an indicator that considers the three pillars of sustainability (environmental, economic and social aspects) in a single indicator to support the decision-making process of stakeholders (i.e. farmers, society and policymakers). On the environmental side, this indicator includes the quantification of the Carbon Footprint, whereas on the socio-economic side it includes the quantification of animal welfare, antibiotics use, technology and workload costs. This indicator is then applied to three Italian case study farms that deal with different aspects of the dairy cattle livestock management.

2. Materials and methods

2.1. Development of the sustainability indicator

A sustainability indicator taking into account the environmental and socio-economic aspects of a livestock farm was developed for multiple reasons: (i) to have a view of the trade-offs of sustainability of dairy cattle farms, (ii) to identify the most beneficial practices on farms that affect both the management and the sustainability points of view, (iii) to facilitate the understanding of the livestock sector, which is a complex and dynamic one (Berckmans, 2014), inclusive of a big number of variables to be considered when making decisions, and (iv) to support in a simple manner the decision-making process of stakeholders and policymakers.

Since this indicator was aimed to evaluate the sustainability trade-offs of livestock activities in the framework of the applicability of European policies, the investigation field was restrained to the environmental concerns of climate change and to the socio-economic concerns of animal welfare and worker workload. Both climate change, animal welfare and attention to the workers' lifestyles are key aspects to livestock activities, therefore, these three aspects were combined in a single indicator resulting in a general sustainability score. In this study, the focus was paid on dairy farms.

Table 1 shows the list of criteria, classes and points used for the assessment of the sustainability indicator, following a multi criteria assessment method.

The three pillars of sustainability were firstly identified: environmental, economic, and social; each of them included a series of criteria defined depending on the final expected use of the indicator. The distinction in classes based on these pillars was completed considering literature findings on dairy cattle farms, and questionnaires to the farmers included in the study. In particular, three classes were defined: a low/bad performing class, an intermediate class, and a good/high performing class. To each of them corresponded a score ranging from 1 (bad class) to 3 (good class). Once the scores were attributed to each criterion, they were summed to obtain the overall points of the sustainability of the farm. To avoid the attribution of subjective weights to the pillars, the weight of each of them was set equal to 1.

2.1.1. Environmental criterion

The environmental sustainability pillar includes as criterion the quantification of the Climate Change (CC) impact category. For this analysis, the method of Life Cycle Assessment (LCA) (ISO 14040 series, 2006) was adopted, in compliance with all studies performed on the environmental impact of milk production in dairy cattle farms (Battini et al., 2014; Mazzetto et al., 2022). In particular, the methodology reported in the Product Environmental Footprint Category Rules for milk products (EDA, 2018) was followed: (i) the Functional Unit selected was 1 kg of Fat and Protein Corrected Milk (FPCM) (4 % fat and 3.3 % protein) produced by lactating cows, (ii) the biophysical allocation method was used to share the impact between milk and meat, (iii) the system boundary was a "cradle to farm gate",[1] (iv) the inventory was filled in through questionnaires by farmers for primary data and through databases for secondary data, (v) the impact

[1] In the alternative scenarios (AS) there was an additional process that included the installed technology of each farm, however it excluded construction and input materials of technology because, although we recognize that this is a limit, data about the materials and energy used for the construction and use were not available in all the cases, therefore, it was decided to not consider it (Pardo et al., 2022; Zhang et al., 2021).

Table 1
Methodological framework of the analysis that shows criteria, classes and points attributed to each sustainability pillar. A reference to each criterion is also given.

Sustainability pillars	Criteria	Class 1: bad/low	Class 2: intermediate	Class 3: good/high	Reference
	Score	1	2	3	
Environmental	Climate change	>1.45 kg CO2 eq./kg milk	1.35–1.45 kg CO2 eq./kg milk	<1.35 kg CO2 eq./kg milk	Mazzetto et al., 2022
Social	Antimicrobial use	>1034 × 10^{-3} DCDvet/year	535-1034 × 10^{-3} DCDvet/year	<535 × 10^{-3} DCDvet/year	Ferroni et al., 2020
	Freedom from hunger & thirst	No	Average	Good	Brambell, 1965
	Freedom from discomfort	No	Average	Good	
	Freedom from pain, injury, disease	No	Average	Good	
	Freedom to express normal behavior	No	Average	Good	
	Freedom from fear and distress	No	Average	Good	
Economic	Cost of investment	High (≥400 €/cow)	Average (200–400 €/cow)	Low (<200 €/cow)	Lora et al., 2020; Morrone et al., 2022; Pfeiffer et al., 2020; personal communications
	Workload of operators	High	Average	Low	Lora et al., 2020

assessment was completed with the Simapro® 8.3.2.0 software Professional version (Pré Consultants 2016) resulting the impact category of Climate Change (CC; kg CO_2eq/kg FPCM). The focus was paid only on the CC impact category because of the relevance in European policies of reducing the impact of human activities on climate change; moreover, this choice was finalized to avoid making too complex the assessment of the sustainability indicator. Finally, in several studies focusing on the environmental impact of livestock productions, similar choices were made (McClelland et al., 2018). The emissions of carbon dioxide, enteric methane, and dinitrogen monoxide are the main contributors to CC, together with milk production and feed ration composition (Pirlo and Lolli, 2019). Since in this study we focused on variating animals' management practices based on a PLF approach, we mostly affected the variables connected with animals' health, welfare, and milk production, thus with those primarily influencing CC.

Three classes were identified for the criterion of CC: bad, average, and good. The threshold among the classes was based on the findings by Lovarelli et al. (2019), Pirlo and Lolli (2019) and in line with the average European values found by Mazzetto et al. (2022).

2.1.2. Social criterion

The social pillar of sustainability was assessed following the approach by UNECE SLCA Guidelines (UNEP Setac Life Cycle Initiative, 2009) considering animals as stakeholders. Following the Classyfarm approach (Classy farm, 2023), which is the recognized list of requirements for proper animal health and welfare recognition in Italian farms, the indicators related to animal welfare and antimicrobial use were adopted in the assessment. Consequently, the five freedoms for animal welfare were considered as indicators for animal welfare, as defined by the Brambell Report (Brambell, 1965; Carenzi and Verga, 2009) and subsequently refined by the Farm Animal Welfare Council (Farm Animal Welfare Council, 2009). These five are: (i) Freedom from hunger and thirst, (ii) Freedom from discomfort, (iii) Freedom from pain, injury, disease, (iv) Freedom to express their normal behavior and (v) Freedom from fear and distress. Also for these freedoms, three classes were identified: no freedom, average level of freedom, good level of freedom, intending that each farm was scored based on the level of each freedom. If the freedom was not included at all in the livestock system it was judged as an issue for animal welfare (a social impact), therefore no freedom was considered; if an average condition describing the most common practices was present, then the average freedom score was considered (compliant condition); finally, if the farm paid particular attention on one or more of the freedoms, then the score was the highest (committed condition).

Moreover, the indication on the use of antimicrobials (AMU) in animals farming was adopted because this aspect is very important in current EU policies aimed to reduce Anti-Microbial Resistance (AMR) (Davis and Sharp, 2020; Rajala-Schultz et al., 2021; Tullo et al., 2019). In line with Ferroni et al. (2020), it was considered that >1034 × 10^{-3} DCDvet/year (Defined Course Doses for animals) lie in the bad case (risky condition), while the good case is when <535 × 10^{-3} DCDvet/year treatments are performed (committed condition).

2.1.3. Economic criterion

The economic pillar of sustainability was evaluated by considering the cost for the investment in the purchase of PLF technology, because this is an important variable affecting the applicability and spread of technology on farms (Abeni et al., 2019; Lora et al., 2020; Morrone et al., 2022; Pfeiffer et al., 2020). The indication on the cost of investment derived directly from questionnaires to farmers and from commercial information. According to Morrone et al. (2022) and Pfeiffer et al. (2020) the quantification of the overall investment costs for PLF is quite complex. Therefore, in this study were defined three quantitative ranges for the extent of investments.

Furthermore, the operators' workload was evaluated, since the presence or lack of manpower and of a satisfactory lifestyle influenced the willingness to work in the sector (Lora et al., 2020). When a lower workload for operators was achieved with technology installed and properly used, it was considered as a positive outcome, as workers could dedicate to other activities (Lora et al., 2020).

For this pillar, therefore, better scores were attributed when a lower investment cost and a lower manpower workload were required. Three classes of scores were attributed to these criteria consistently with the other criteria, but with an opposite trend (1 = expensive/high, 2 = average, 3 = affordable/low).

2.2. Description of the case study farms

This study lies in the framework of the National Project "Smart Dairy Farming – innovative solutions to improve herd productivity" financed by the Italian Ministry of Education, University and Research; here, three dairy cattle farms were monitored from 2019 until 2022 to evaluate improvements to the farm management based on the introduction of PLF tools and on improved animal management. The major issues that were addressed are:

(i) heat stress, studied in a farm located in the Po Valley (Northern Italy),
(ii) detection of estrus events, in a farm located in the Sicily Region (Southern Italy),
(iii) free access of cows to external areas, in a farm located in the Po Valley (Northern Italy).

Farms included in this study were identified based on the Project activities and availability of farmers to carry out the trials. The following sections are organized describing the 3 farms and the related intervention areas based on the scope of the project.

2.2.1. Heat stress detection

More and more frequently, farmers must tackle with heat stressing conditions, which is a widespread issue in many regions (Herbut et al., 2018; Polsky and von Keyserlingk, 2017), among which the Po Valley area (Northern Italy) where summer peak temperatures exceed 35 °C and relative humidity is often above 70–80 % (Bonaldo et al., 2023). By combining temperature and relative humidity, the Temperature-Humidity Index (THI) is calculated (LCI, 1970), which is an index used as a proxy of satisfactory barn environments. THI strongly influences dairy cow welfare, health (Cook et al., 2007; Galán et al., 2018), fertility, and productivity (Ji et al., 2020a,b; Polsky and von Keyserlingk, 2017). To deal with heat stress (commonly observed from spring to autumn), animals tend to stand for a longer time than usual to dissipate their heat load (Herbut et al., 2019), at the expense of welfare and productivity (West, 2003). Fans and sprinklers are the most adopted tools on farms to cope with heat stress as they improve the internal barn environment (Ji et al., 2020a,b).

For this project, one dairy cattle farm of Northern Italy was selected and monitored for two years to investigate the response of dairy cows to environmental conditions in summer. The barn hosted 1000 dairy cows of Italian Holstein breed in a recently renovated open barn equipped with fans and sprinklers. In particular, the barn and herd were already present, but the new owner decided to introduce technological support tools on the farm. Therefore, first in 2021 fans were installed to improve the internal environment. Then, in 2022 a control unit was implemented, making fans connected with environmental sensors of temperature and relative humidity and making functional the automatic start of fans at the proper environmental conditions (threshold based on barn temperature). In addition, in 2021 animals were equipped with commercial pedometers (AfiTagII, Kibbutz Afikim, Afimilk, Israel) positioned on their hind leg to collect and analyze behavioral data (i.e. activity, rest, rest bouts).

As reported in Abeni et al. (2019), Andriamandroso et al. (2017), Fan et al. (2022), Riaboff et al. (2022) and Stygar et al. (2021), the adopted abovementioned sensors are user-friendly, reliable, easy to use, and with low cost.

2.2.2. Detection of estrus events

A second big issue of dairy cattle farming is the well-known aspect of fertility (Pryce et al., 2004) that, together with proper estrus detection and prompt insemination are among the major problems of current dairy farming. Identifying, and promptly and successfully inseminating cows permits to avoid increased costs of vets for re-fertilizations and of feed, as well as low milk production when the lactation period gets prolonged (Bell et al., 2011). Fertility and estrus detection are also affected by heat stress, because in such distress the fertility rate has been found to reduce significantly (Ji et al., 2020a), especially in highly productive cows (Galán et al., 2018; Correa-Calderon et al., 2004). In addition, silent estrus and nighttime estrus are more complex to observe (Arcidiacono et al., 2020) and become more frequent with heat stress. To avoid that farmers miss the observation of increased animal activity, thus miss the insemination, detecting estrus with sensors that monitor animal activity avoids errors due to the discontinuous eye-monitoring. This issue is particularly relevant in Southern Italy, where high summer temperatures significantly reduce the activity and fertility of dairy cows.

In this case study, a dairy cattle farm located in Sicily (Southern Italy) was monitored by installing prototype pedometers on the hind leg of dairy cows to evaluate its potentialities in detecting estrus events, especially at nighttime, by focusing on standing and walking behaviors (Porto et al., 2022). Like the previous case, the pedometer registers the animal behavior; an unexpected variation in behavior was considered as a symptom for estrus, illness, or distress (Herbut et al., 2018). Being prototype tools, they were installed only on 5 lactating cows to test their functioning; moreover, being aimed to detect the estrus window and not the animal behavior for a long time, they were installed on animals for 1 to 3 months to detect the heat event, then getting approvals from the farmer and vet. Afterwards, they were uninstalled to be used on other animals. The farm was quite small, farming in total 56 lactating cows of Italian Holstein breed. Hence, although few sensors were available, 9 % of the herd was monitored.

Like in the previous case, pedometers are among the most used tools in Italian farming systems (Abeni et al., 2019), and they are simple, user-friendly, low-cost, and technologically sound; moreover, farmers can achieve significant improvements with their use (Stygar et al., 2021).

2.2.3. Access to external areas

In regard of the welfare and health of animals and of the consumers' perspective about animals living conditions, knowledge about the benefits of providing cows free access to pastures or external paddocks can be of interest (Arnott et al., 2017; Peira et al., 2020; Stampa et al., 2020). A free access to external areas can bring benefits to reduce the biodiversity loss, to improve the consumers' vision of livestock farms and to identify differences in animal behavior. Moreover, such areas can be a valid option to better approach the natural behavior of cows (Charlton and Rutter, 2017). This typology of livestock farming is very interesting but also complex to establish in practice, especially in highly intensive livestock areas such as Po Valley, where the availability of an external area for animals' pasture is rare (van den Pol-van Dasselaar et al., 2020).

This case study investigated the effects on animal welfare and performance of providing high yielding dairy cows with free-choice pasture access during their dry period. This test was carried out in a dairy cattle farm in Northern Italy. During the dry period, cows were randomly assigned to two different treatments: 1) housing with free-choice access to an exercise pasture or 2) housing continuously without any access to the outdoors. Once enrolled, the animals remained in the treatment group until calving, after which they were all mixed and housed without any outdoor access. All animals enrolled were monitored both before calving (when exposed to different treatments) and during the first 100 days-in-milk (DIM) of the following lactation (when mixed all together).

The feeding and ruminating behavior of cows was continuously recorded with a collar-based sensor (AfiCollar, Kibbutz Afikim, Afimilk, Israel). All cows were inspected monthly to assess health, cleanliness, and body condition score. After calving, milk yield was recorded for each cow at each milking with automatic milk meters in the parlor (Afimilk MPC, Kibbutz Afikim, Afimilk, Israel). Milk quality and estimated 305-d milk yield were measured during monthly tests performed by the Italian Breeders Association (Associazione Italiana Allevatori, Rome, Italy).

The collar-based accelerometers used have the same technological advantages of the pedometers (see Sect. 2.2.1), and the same advantages can be listed for the automatic milk meters, since they are all reliable and easy to use. Finally, this trial included specific monthly health inspections that required dedicated manpower.

3. Results

3.1. Results of farms' performance

3.1.1. Case study on heat stress

Regarding farm A (monitored barn environment and animals' behavior and health), in respect to 2021 (fans with manual starting), in 2022 (automatic functioning of fans) the average milk yield increased by about 20 % during the warmest months in summer, when THI was close to/above the thresholds of 68 (first alert) and 72 (alert). In particular, in 2021, THI between May and September ranged between 67.9 and 76.5; in 2022, it was between 66.4 and 80.1, as average of the same period. Although the exceptional heat wave registered in 2022, the THI in the barn was registered slightly higher (1–5 %) in 2022 than in 2021 only in July and August. Furthermore, milk yield and the other behavioral and health indicators were not negatively affected by THI.

Specifically, milk production was higher in 2022 (40.8 ± 7.3 kg/d per cow) than in 2021 (33.1 ± 3.8 kg/d per cow), apart from January and May which had the same result as 2021. Concerning health issues, animals in 2022 were much healthier (except for January, animals diagnosed with pathologies were 27 % lower in 2022 than in 2021), and the same occurred for the treatments performed on the animals and the medicines used (on average, −3 % in 2022 than in 2021). Only in regard of the treatments, there was an increased number in January (in line with the diagnosis and milk yield and therefore due to a common reason), April, May and August 2022. No medicines were used and registered from August 2021 on. The behavior of animals showed an increased average activity, rest, and rest bout duration in 2022, except for January and May when the values were lower than 2021. In summer 2022, the rest time and rest bout duration were longer (328 ± 38 min and 5.6 ± 0.5 min, respectively) than in 2021 (283 ± 2 min and 4.9 ± 0.1 min, respectively), at the benefit of animals' welfare and health.

3.1.2. Case study on estrus detection

In farm B (estrus detection with continuous real-time monitoring), 5 dairy cows (9 % of the herd) were monitored. The pedometers were installed for one month before and after estrus and resulted data on animals' activity. At the same time, milk production was registered for the same period and continued for the subsequent month when the pedometers were uninstalled. These two periods cannot be compared since the days in milk and seasonality affect milk production, but the pedometers had the specific aim to detect the estrus event. The average milk production of the monitored cows in the whole period was 35.1 ± 7.4 kg/d when pedometers were installed, and 38.2 ± 7.2 kg/d in the following month (uninstalled pedometers).

All the estrus events detected by the pedometers were validated both by the farmer (by visually identifying the signs of estrus) and by the veterinarian (via milk analyses); however, there cannot be certainty regarding the successful subsequent pregnancy. Estrus detection resulted a good method to promptly generate the alert but similarly to most PLF tools it requires a prompt and valid human intervention. The monitored farm is quite small in herd dimension (lactating cows, n = 56), and therefore the technological benefit is more limited than in a big herd; however, the farmer highlighted the benefit of having sensors for detecting estruses at nighttime. Therefore, the pedometer effectively supports the farmer, valuing the information provided by PLF tools (Rojo-Gimeno et al., 2019) with no influence by the herd dimension. Instead, the disadvantage could be related to the fact that with a small herd dimension the fixed costs for the installation of such sensors result more impactful than in a bigger herd (Morrone et al., 2022; Pfeiffer et al., 2020).

3.1.3. Case study on access to external area

The experiment carried out in farm C (free access to external area) suggested that providing free-choice pasture access during the dry period can positively affect welfare, health and performance of dairy cattle and may represent a desirable practice for confinement-based operations. Results give suggestions on an improved herd management, while no difference in installed PLF tools was present. In particular, cows that had free pasture access were cleaner and healthier (hock lesions) than those in the control group, while no differences in locomotion and body condition score were found. By analyzing animal activity with the neck-collars, the cows with free pasture access during the dry period spent significantly more time feeding (458 ± 11.1 min/d) than the control group (414 ± 12.1 min/d). Although the difference was not statistically significant, the cows in the treatment group (353 ± 10.4 min/d) also tended to have higher feeding time than the control (325 ± 11.2 min/d) after calving.

Allowing free pasture access during the dry period affected milk production during the following lactation (+5 % of milk yield). Cows that were in the treatment group had a higher daily milk yield (38.9 ± 1.04 kg/d per cow) and lactation milk yield (10,124 ± 244 kg) than those in the control group (37.0 ± 1.12 kg/d per cow; 9276 ± 268 kg). Instead, the different treatment during the dry period did not produce significant effects on the milk composition (SCC, milk fat, and milk protein). Again, the Value of Information plays a role, since these remarks could be obtained just after a detailed monitoring of the herd with the PLF tools.

Table 2
Results of the main performance indicators and of Climate Change impact category (in bold) in each scenario.

Parameters	Unit	Farm A – heat stress		Farm B – estrus		Farm C – external access	
		BS	AS	BS	AS	BS	AS
Climate change	**kg CO_2eq/kg FPCM**	**1.31**	**1.24**	**1.83**	**1.68**	**1.65**	**1.54**
Dry matter intake	kg DMI/d	24.4		26.2		24.8	
Milk yield	kg milk/d	33.2	35.2	30.9	32.5	30.6	33.1
Fat	%	3.85	3.85	3.90	4.10	4.06	3.99
Protein	%	3.39	3.39	3.35	3.45	3.20	3.22
Corrected milk yield	kg FPCM/d	32.8	34.8	30.6	33.3	30.6	32.8
Dairy efficiency	kg FPCM/kg DMI	1.34	1.43	1.17	1.27	1.23	1.32

3.2. Results of the sustainability indicator

The sustainability indicator was quantified in each farm both for the traditional farming system with the management practices in force at the beginning of the project (Baseline Scenario, BS) and for the improved farming with PLF tools/management improvements suggested within the project (Alternative Scenario, AS). A score was attributed to each criterion listed in the indicator for both scenarios (BS and AS) of each farm (A, B and C).

Fig. 1 reports schematically the main differences among the case study farms, distinguishing in scenarios without (BS) vs with PLF/improvement (AS). In particular: without (BS) and with (AS) pedometers installed on dairy cows plus environmental sensors and milk meters for the study on heat stress (Farm A); the same with focus on pedometers for the study on estrus detection (Farm B); and without (BS) and with (AS) access to free pasture for the study on pasture use (Farm C) in which neck-collars and milk meters were adopted for the monitoring.

3.2.1. The environmental criterion

The results of the Climate Change impact assessment of the studied farms are reported in Table 2 for BS and AS. Average daily dry matter intake (kg DMI), milk yield (kg/d), fat and protein content (%), and milk yield corrected as fat and protein corrected milk (kg FPCM) as used for

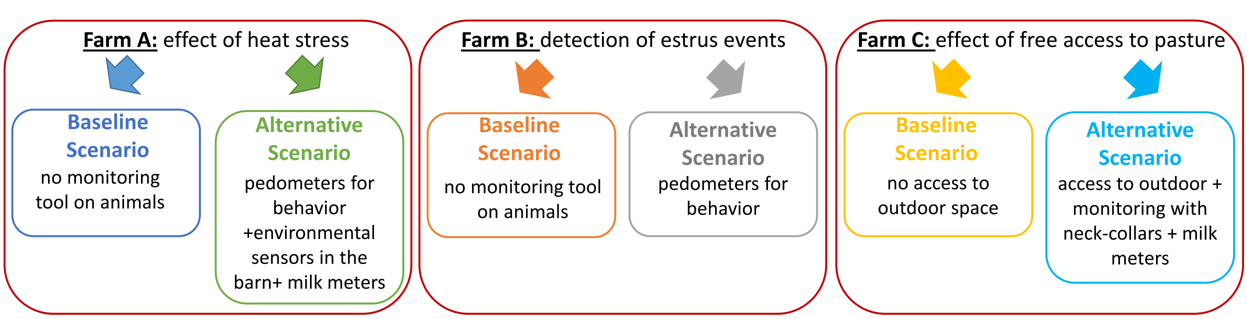

Fig. 1. Differences between scenarios and farms assessed in this case study.

Table 3
Social criteria in each studied farm for BS and AS. Notes: " + " means it is positive for the case study farm (proactive/committed issue); "-" means that the farm/PLF used does not bring any specific improvement to it (compliant issue); "–" means that the farm/PLF used has a risky behavior towards this issue (risky issue).

Criteria	Farm A		Farm B		Farm C	
	BS	AS	BS	AS	BS	AS
Antimicrobial use	+	+	+	+	+	+
Freedom from hunger & thirst	-	+	-	-	-	-
Freedom from discomfort	--	+	-	-	-	+
Freedom from pain injury disease	-	+	-	-	-	+
Freedom to express normal behavior	-	-	-	-	-	+
Freedom from fear and distress	-	-	-	+	-	-

the environmental assessment are reported. Then, also the dairy efficiency (DE), which is the efficiency in transforming the ingested dry matter feed into corrected milk (kg FPCM/kg DMI) is quantified as an efficiency indicator.

Some differences were found in the main production and management characteristics of the farms, which then reflect on the climate change results. Furthermore, also seasonality may affect CC results. For this reason, each farm should be studied as a specific case.

Since these results are farm specific, more than the absolute value, it is interesting to note the relative reduction (%) of the CC achieved with the different practices in the baseline and alternative scenarios. An impact reduction is achieved in all the AS cases; therefore, by introducing some improvements to the traditional barn management by dedicating more attention to animal welfare and health, CC can reduce. In particular, the reduction of environmental impact between BS and AS in these farms is equal to 6 %, 9 % and 7 % in farms A, B and C, respectively. The results are in line with expectances because commonly, if no changes in the inputs used are present, when an increased milk production – and increased Dairy Efficiency - was registered, the environmental impact on CC would reduce (Balaine et al., 2020; Pirlo and Lolli, 2019). Although Pardo et al. (2022) studied dairy goats, in their study on the environmental impact of dairy goat farms before and after the use of PLF, they achieved reductions of CC of 11 % when PLF-farms were compared with no-PLF-farms, which is in line with our findings.

3.2.2. The social criterion

Table 3 shows the results on the social pillar of sustainability. In this table, for each farm, the 5 freedoms of animals and the use of antibiotics are considered.

Achieving good performances with animal welfare entails a wide number of indirect advantages also on the health and productivity. Without/with reduced heat stress, for example, animals behave normally, are less subject to injuries/illnesses (e.g., mastitis, lameness) and do not have milk losses over time. Respect to the detection of estrus, instead, a good result on welfare aspects involves increased efficiency, with no need to further fertilize, less vet costs, and less fear/distress to animals caused by the vet intervention. In farm C, the access to external areas allows cows to better express their natural attitude, reduce lesions and discomfort, improve productivity, health, and reduce the AMU.

3.2.3. The economic criterion

Considering the cost of technology for the farm and the workers' workload, Table 4 reports the results of this component of the sustainability at farm level. Farms without the installation of sensors or monitoring tools did not have any advantage on the technological point of view, therefore no score was attributed to them in the general indicator. In this case study, AS and BS highlight differences in the economic criterion because the cost of PLF is an additional cost to the BS option.

The sensors used to monitor the barn microenvironment (temperature and relative humidity) and animal behavior (lying, standing, walking, feeding, ruminating) and productivity are the most reliable technologies available on the market (Chapa et al., 2020; Stygar et al., 2022). Their costs are also quite small, and the easiness of installation and use is high (Pfeiffer et al., 2020). Finally, their support with the reduction in workload (time dedicated to observing animal behavior and making actions) is high for accelerometers (i.e. pedometers and neck-collars) and milk meters (Lora et al., 2020; Stygar et al., 2022), and is medium-high for the environmental monitoring, depending on the presence or lack of the automatic activation of fans and sprinklers (Ji et al., 2020a). In particular, when tools substitute workers in the observation and alarm them if needed, help to save time and improve the observation quality (no subjectivity or missed observation).

3.2.4. The sustainability indicator

The results achieved on each pillar of the sustainability assessment were combined in the indicator of sustainability.

To avoid attributing subjective weights, the weight of each indicator was set equal to 1. Table 5 reports the results of each case study farm (BS and AS) based on the performance of each indicator. The scores attributed to each indicator were summed to obtain the overall points of the sustainability of the farm.

In all the three farms, AS achieves better performances on all or almost all the sustainability pillars. BS did not receive any points on the economic criterion related with "cost of the investment" because no tool was present, therefore no score was attributed. Another aspect to underline is that among the criteria, Climate Change improved from BS to AS in all farms, but based on the thresholds defined in the classes, the improvement was not sufficient to make farms change the class (and score), therefore no improvement can be appreciated on this aspect. The reason is that to improve CC, also other aspects of farming need to improve, and in the farms B and C, the feeding choices affected considerably the high CC result. This result is in line with Balaine et al. (2020) who did not find significant improvement in the GHG reduction when technology was installed on Irish dairy farms.

4. Discussion

This study was aimed to show the pros and cons of introducing more attention to the management of dairy cattle farms with the use of PLF, by evaluating its effect on the three sustainability pillars and by trying to quantify these benefits through a simple sustainability indicator that could be adopted by policy and decision makers. With PLF the most desirable result is to measure, collect and store data to give value to such information (e.g., detect and avoid undesired conditions, improve the efficiency of the system) and improve animal living conditions (Rojo-Gimeno et al., 2019; Schillings et al., 2021). Considering that such an evolution on farm brings also other collateral improvements, it was interesting to assess the general environmental and socio-economic aspects using 3 dairy farms as case study, finally allowing some indications for the assessment of other farms on a national/international level. A similar approach was adopted by Balaine et al. (2020) who tried to connect technology with a sustainable

Table 4
Sensors evaluated for this study with the related characteristics and class in which they appear in the indicator.

Criteria	Type of sensor/device		
	Device to monitor the microenvironment (Farm A)	Pedometer/neck-collar to monitor the animal behavior (Farm A, B, C)	Milk meter to monitor milk production (Farm A and C)
Cost	<200 €/cow	<200 €/cow	<200 €/cow
Workload (reduction)	Average	High	High

Table 5
Scores to the sustainability assessment of the three farms. To each criterion a score from 1 to 3 based on the values defined in Table 1 is attributed. The overall result (in bold) is the sum of each score.

Sustainability pillar	Criteria	Scores	Farm A		Farm B		Farm C	
			BS	AS	BS	AS	BS	AS
Environmental	Climate change	1–3	3	3	1	1	1	1
Social	Antimicrobial use	1–3	3	3	3	3	3	3
	Freedom from hunger & thirst	1–3	2	3	2	2	2	2
	Freedom from discomfort	1–3	1	3	2	2	2	3
	Freedom from pain, injury, disease	1–3	2	3	2	2	2	3
	Freedom to express normal behavior	1–3	2	2	2	2	2	3
	Freedom from fear and distress	1–3	2	2	2	3	2	2
Economic	Cost of investment	1–3	n.a.	3	n.a.	3	n.a.	3
	Workload of operators	1–3	1	3	1	3	2	2
Sustainability score			**16**	**25**	**15**	**21**	**16**	**22**

intensification of Irish milk production identifying the benefits of technology on dairy farms.

From the results of this study emerges that installing monitoring tools on farm does not bring benefits only on one aspect, but has a wider effect on the animal, as also suggested in other studies (Bell et al., 2011; Charlton and Rutter, 2017; Dominiak and Kristensen, 2017) and on the environment and society. Therefore, an important consideration is that by focusing on one/few aspects of farming and improved management, the sustainability effect can have a bigger extent, which needs to be understood primarily by the farmer and the policymaker. In agreement with Balaine et al. (2020), PLF can be considered a win-win-win solution if properly used.

This study has some limits to point out: first, the farms were selected to test different aspects of dairy farming, therefore they could not be compared among each other; second, only three farms were assessed, which is a quite small sample; however this indicator can be considered as a preliminary attempt to quantify the dairy farm sustainability in a simplified and user-friendly manner to be used by farmers and policymakers; third, regarding each pillar, other indicators could have been considered (e.g., other environmental impact categories acidification, eutrophication, particulate matter formation, other stakeholders for the social impact, other economic indicators, etc.), however, it was decided to focus on the selected ones due to the framework and organization of the project within which they were studied.

Finally, two main considerations emerge on the different farming typologies: on one side appears the positive effect of a highly technological farm with a big herd, and on the other side appears the positive effect of giving animals the free choice to access a pasture area. Both solutions can coexist on a national/international level, since in both cases the efficiency and improved farming can make the difference in respect with the traditional farming practices. When animals are healthy and live in conditions adequate to the welfare, they usually get less ill, thus need less medicines, less vets' interventions, and finally have lower losses in milk production than animals living in unsatisfactory environments (Dallago et al., 2021; Leliveld and Provolo, 2020; Tullo et al., 2019; von Keyserlingk and Weary, 2017). This itself improves the sustainability (Froldi et al., 2022) and needs to be promoted among stakeholders, including decision-makers and consumers, which is why this simplified sustainability indicator could be spread among farmers, consumers and decision-makers that are unaware of the potential benefits of some practices on farm (Ernst, 2019; Subramanian et al., 2018). In this regard, giving proper information to consumers and society is one key role of researchers and policy makers, since consumers can deeply affect the market (Stygar et al., 2022) and penalize with malicious campaigns the agriculture and livestock productions. This indicator could be further improved by taking into consideration not only PLF and improved management at the barn level, but also other aspects of dairy farming (e.g. manure management, air quality), using it on a wider perspective. In particular, it may allow policy makers to quantify the effect of future policies on farms and therefore identify those policies that better help achieve the EU sustainability goals (Garnett, 2009; Kipling et al., 2019) and better convince farmers in investing in technology (Morrone et al., 2022). Given its general and simple framework, the developed indicator can be used both on a regional and national level to better understand the effect of promoting measures locally.

5. Conclusions

In this study we evaluated the sustainability of 3 dairy cattle farms located in three different areas of Italy. The key point was to take into consideration not only the impact on climate change as one environmental sustainability indicator, but also the socio-economic criteria, evaluating the technology as a means for improvement of livestock farms. The aim was to develop an indicator easily understandable and adoptable by policy and decision makers to detect the main potentialities and drawbacks of future policies and to support farmers towards understanding the effects of innovation and improved knowledge achievable with PLF. As results from this study, technology on farm can lead to significant improvements on all aspects that build up the sustainability framework, although with different effects on the different criteria. Each region or nation could provide policy makers, stakeholders, and farmers with this tool, enabling them to best understand the potentialities of single farms, to make the most suitable decisions based on local potentialities and give the opportunity to different farm typologies to coexist and integrate with the territory.

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CRediT authorship contribution statement

Daniela Lovarelli: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Lorenzo Leso:** Software, Formal analysis, Investigation, Writing – review & editing. **Marco Bonfanti:** Software, Formal analysis, Investigation, Writing – review & editing. **Simona Maria Carmela Porto:** Resources, Writing – review & editing, Supervision, Project administration. **Matteo Barbari:** Resources, Writing – review & editing, Supervision, Project administration. **Marcella Guarino:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

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

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