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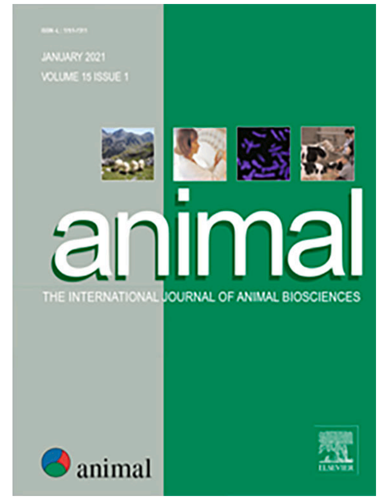

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Review: Exploring the use of Precision Livestock Farming for small ruminant welfare management

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Highlights

- More than 80 main welfare issues for sheep and goats' systems were identified
- Stakeholders' engagement gave an overall welfare issues prioritisation by species.
- Four broad categories of welfare indicators based on welfare issues were defined.
- 24 technologies potentially able to monitor welfare indicators were identified.
- Very few technologies identified could be used currently on commercial farms.

Abstract

Small ruminant (sheep and goat) production of meat and milk is undertaken in diverse topographical and climatic environments and the systems range from extensive to intensive. This could lead to different types of welfare compromise, which need to be managed. Implementing Precision Livestock Farming (**PLF**) and other new or innovative technologies could help to manage or monitor animal welfare. This paper explores such opportunities, seeking to identify promising aspects of PLF that may allow improved management of welfare for small ruminants using literature search (2 reviews), workshops in 9 countries (France, Greece, Ireland, Israel, Italy, Norway, Romania, Spain, and the United Kingdom) with 254 stakeholders, and panels with 52 experts. An investigation of the main welfare challenges that may affect sheep and goats across the different management systems in Europe was undertaken, followed by a prioritisation of animal welfare issues obtained in the 9 countries. This suggested that disease and health issues, feed access and undernutrition/malnutrition, maternal behaviour/offspring losses, environmental stressors and issues with agonistic behavioural interactions were important welfare concerns. These welfare issues and their indicators (37 for sheep, 25 for goats) were categorised into four broad welfare indicator categories: weight loss or change in body state (**BWC**), behavioural change (**BC**), milk yield and quality (**MY**), and environmental indicators (**Evt**). In parallel, 24 potential PLF and innovative technologies (8 for BWC; 10 for BC; 4 for MY; 6 for Evt) that could be relevant to monitor these broad welfare indicator categories and provide novel approaches to manage and monitor welfare have been identified. Some technologies had the capacity to monitor more than one broad indicator. Out of the 24 technologies, only 12 were animal-based sensors, or that could monitor the animal individually. One alternative could be to incorporate a risk management approach to welfare, using aspects of environmental stress. This could provide an early warning system for the potential risks of animal welfare compromise and alert farmers to the need to implement mitigation actions.

Keywords: welfare indicators, technologies, sheep, goats, stakeholders

Implications

Small ruminant production systems are varied and lead to different welfare compromises, often difficult to assess or monitor. Precision Livestock Farming, although in its infancy for application to small ruminant systems, could provide opportunities for small ruminant welfare management. Literature searches and prioritisation of welfare issues for small ruminants helped identify a potential shortlist of technologies promising for small ruminant welfare management. However, as yet, most of them are not specific enough, and can only alert farmers to the need of implementing mitigation actions.

Introduction

Precision Livestock Farming (**PLF**) is widely adopted in the management of high value animals (Carpentier et al., 2018; van Hertem et al., 2018), largely for production purposes, but is also being used for assessing and managing welfare (e.g. Norton et al., 2019; Schillings et al., 2021; Gómez et al., 2021). However, PLF is rarely adopted in sheep and goats, or in extensive management systems, for any purpose (Caja et al., 2020). This is despite the potential significant welfare and production efficiency advantages that could be achieved by applying PLF in these contexts, which can increase surveillance of animals when the farmer is not present and provide individual monitoring within large flocks. Commercial applications of PLF solutions are more common in intensive large-scale farms (Simitzis et al., 2022). Although variable across Europe, sheep and goat farms are often at small scale and their owners are generally conservative, and reserved towards new technologies (Rieple et al., 2018). Moreover, poor technological infrastructure (e.g., electricity, telephone, connectivity and internet networks) and other financial barriers limit the regular use of PLF in small ruminant production systems (Vaintrub et al., 2021). The use of PLF technologies could be more attractive to sheep and goat farmers if stakeholders, including researchers, consultants and knowledge transfer personnel demonstrate the beneficial impact that these systems have on welfare and efficiency, leading to more sustainable and profitable units (Wishart, 2019).

Animal welfare is increasingly considered to be about the animal's experience, considering the individual sum of suffering or pleasure that accrues to the individual over the course of its life (Mellor et al., 2020). However, livestock, particularly those which provide a lower financial return (such as sheep and goats), are often managed as a group, flock or herd and only average welfare state might be considered (e.g. average values for the group in terms of body condition and milk yield might determine the feeding management). However, this may mean that some individual animals may experience quite poor welfare, even if the average animal is in relatively good welfare. Therefore, a PLF approach to welfare monitoring and management in these species could enable individual animals to be identified within the group, so that feed, health care or other aspects linked to welfare can be individualized.

To date, the development and uptake of PLF technologies and tools in the small ruminant sector are limited, even though since 2010 all small ruminants in the European Union are individually identified with an electronic tag following the 2004 EU legislation (Council Regulation (EC) No 21/2004), and 64% of sheep farmers considered PLF as an opportunity (Gautier et al., 2019). However, it is mainly large farms that have acquired the necessary equipment which are likely to be able to take advantage of added value from compulsory electronic identification (Gautier at al., 2019). Nonetheless, PLF technologies available in other species could potentially be used for small ruminants (Halachmi, 2015).

Many of the challenges to welfare in small ruminant systems (e.g. lack of supervision and disease treatments, use of painful procedures to ease management, long distance transport to slaughter; Rioja-Lang et al., 2020) arise from the constraints imposed by the environment and areas in which these animals are reared – often remote or topographically and climatically challenged (EFSA Panel on Animal Health and Welfare, 2014). However, these are also the main areas where a PLF approach could improve welfare management and so mitigate such welfare issues. For example, a major benefit of sensor-based monitoring would be as an early warning system to detect disease or welfare compromise, earlier than would be feasible from human observation, particularly with reduced labour availability. Precision Livestock Farming could also offer the possibility to provide individualised care to animals within large flocks or herds, without the need to remove them from the social group.

In recent years, flock and herd sizes have increased, therefore small ruminants are increasingly being managed within larger groups and infrequently handled (particularly in extensive and meat production systems). In dairy systems, while the animals are handled more frequently (due to milking) than in meat systems, this only lasts during lactation for dairy sheep and dairy goats, especially in extensive systems. The increasing risk of unacceptable animal welfare due to fewer interactions between farmers and their animals (EFSA Panel on Animal Health and Welfare, 2014) is of concern and worthy of further consideration. New PLF technologies may compensate for this trend, helping farmers to individually monitor the behaviour and productive traits of their animals, especially with animal-based sensors. Systems, such as digital scales capable of automatically identifying animals (González-García et al., 2021), milking machines with automatic flowmeters or Global Positioning System (**GPS**) tags/collars able to remotely track the animal position and behaviour at pasture (Umstätter et al., 2008; Sarout et al., 2018) could be used. Some devices are already available on the market, although they are often not integrated with each other, can be poorly validated and data are often undermined and underexploited with reference to welfare issues. The validation of some of these existing technologies or of those that are still at lower Technology Readiness Level (**TRL**), may benefit animal welfare but could also be the key to increasing production efficiency. However, application of PLF to improve welfare does also carry a number of other risks, including an over-reliance on technology, spending less quality time with the animals, and losing animal-oriented husbandry skills (Tuyttens et al., 2022).

This paper explores the potential of using PLF tools for welfare management of small ruminants. The objectives of the current study were i) to prioritise the main welfare issues that were of concern for European producers/stakeholders of meat and dairy sheep, and dairy goats; and ii) to determine which PLF technologies were most likely to be suitable for managing these welfare conditions, in either extensive or intensive production systems.

Material and Methods

Study areas

This study was undertaken in 9 countries (France, Greece, Ireland, Israel, Italy, Norway, Romania, Spain, and the United Kingdom), each having either one, two or three small ruminant production types (i.e., meat sheep, dairy sheep, dairy goat) (see Fig. 1). These countries represent most of the small ruminant population (sheep and goats) in Europe, with 71 million heads in the EU (Eurostat, 2021) and an additional 34 million heads in Norway, Israel and the United Kingdom (FAOSTAT 2018).

The 9 countries also cover the diversity of climatic conditions and European production systems i.e. meat sheep in Northern Europe, mainly based on extensive grassland environments (Ireland, Norway and the United Kingdom); meat sheep in Mediterranean environments (Spain, France, Israel); dairy sheep in Continental Europe (Romania) and in Western/Mediterranean environments (Spain, France and Italy); dairy goats in Northern Europe (Norway) and in Mediterranean environments (Spain and Greece), both intensive/extensive.

Initial welfare prioritisation (literature review and expert panels opinion)

An initial literature review was undertaken (Fig. 2) to determine the main welfare issues for sheep and goats across all the systems in use in the European Union (using the systems as defined by EFSA 2014 for sheep). The Five Domains model of welfare assessment (Mellor et al., 2020) was used as a starting point. Considering that the 'mental state' is the result of the interplay between the other 4 domains, we have focused our attention on them, with searches for welfare domain ('nutrition', 'health', 'environment', 'behaviour') and the species name ('sheep' or 'goat' and including 'ewe', 'ram', 'lamb', 'doe', 'buck' and 'kid' as alternative terms) as well as 'welfare' more generally. At this scoping stage, to assemble a full list of potential welfare issues, all papers that covered at least one aspect of welfare and provided at least one related outcome were included. The initial screening of welfare issues resulted in more than 80 separate welfare concerns mentioned in the literature for both sheep and goats, when considered as issues affecting animals at different ages and at different stages of production (Supplementary Material S1). These issues were then refined by presenting the lists to experts in each country (n= 34: France= 8; Ireland= 4; Italy= 5; Israel= 2; Norway= 2; Romania= 2; Spain= 5; United Kingdom= 6) to ensure that the main welfare issues for different countries were included, and to ensure that the list was as comprehensive as possible (Fig. 2, Step 1a). These experts were animal and welfare scientists (n= 17), veterinarians (n= 12) and farm advisors (n= 5) with knowledge of the production type and/or purpose, and of local welfare issues. The experts conducted an initial prioritisation to focus on the issues affecting sheep or goats dependent on production purpose (meat or dairy) and management system (shepherded; intensive; semi-intensive; semi-extensive; extensive; very extensive), considered most relevant to their country. This process was designed to reduce the number of issues to between 30-40 per species for each management system, and to streamline the process before stakeholder engagement to determine the final prioritisation. For example, for indoor management systems, typically predation was not considered a relevant indicator and was not included in the prioritisation in these systems. Similarly, for dairy systems, the mother-offspring relationship was not included in the list of indicators as lamb or kid separation from the mother is an integral part of these systems and thus this issue could not be properly considered. For each country, the most important welfare issues, the stage in the production system where these would be most likely to occur, and the most commonly used or validated animal-based welfare indicators were identified.

Stakeholders' engagement and final prioritisation

In each of the nine countries, a group of stakeholders was assembled (Fig. 2; Step 2) which included in total: farmers (91), academics (59), consultants and representatives of farmer associations (57), welfare associations (1), veterinarians (16) and farm industry representatives/levy boards/value chain (30). Each country tried to include at least one representative from each of the above categories where applicable. The stakeholders participated in a series of national workshops, which were held in each country in Spring 2021, to validate their welfare issues prioritization (Table 1). Prior to the workshops, participants were sent the same disclaimer/consent form, including anonymity assurances, translated in their own language.

Within each country, the same protocol was followed using an **OPERA** (Own reflexion, Pairing, Explanation, Ranking, Arranging) procedure (Slaen et al., 2003) at the stakeholder workshops, to develop individual, small groups and final lists of welfare priorities for each production system, as seen by stakeholders. This method involved six steps as follows:

1. Introductive discussion: the participants were presented the shortened list of welfare issues pertinent to their country and production system, as well as an introduction to the study's objectives.
2. Silent reflexion: the participants were asked to think individually about the 3 most important welfare issues from the list provided.
3. Think sharing: the participants were put in smaller groups of 4-5 and asked to discuss and share their welfare priorities.
4. Roundtable: feedback to their small group.
5. Ranking: the small group was asked to reach consensus on the 3 most important welfare issues, based on their discussions.
6. Wrap-up and plenary discussion: each small group provided feedback on their rankings and a final consensus was reached for the whole group.

Overall prioritisation by species

The outcomes from the stakeholders' workshops provided a list of country-specific and system-specific welfare issues. Nine groups of stakeholders provided prioritisations across the 9 countries for sheep, and 3 groups of stakeholders for goats (Table 1). In total, prioritisations were considered for extensive sheep (4 workshops, plus 2 mixed system, total n= 6), intensive sheep (5 workshops, plus 2 mixed systems, total n= 7), intensive goats (2 workshops, n= 2) and 1 extensive goat system (1 workshop).

For each welfare issue, at each workshop, a ranking was produced depending on whether the issue was considered to be of:

1. high importance (ranked 1 as the most important by the majority of participants),
2. medium importance (ranked either as the 2nd highest issue, or a mix of high priority issues by the majority of participants),
3. less importance (ranked the 3rd most important issue by the majority of participants, or a mix of medium and lower priority issues).

The overall prioritised issues were summed across countries within system (times cited/number of workshops), and the frequency with which each issue was ranked of high importance in any workshop (number of highest rankings).

Creation of broad categories of welfare indicators

Once the welfare issues had been prioritised by species, their corresponding animal-based welfare indicators were identified and collated using the existing literature (Fig. 2). The main specific animal-based welfare indicators could be further categorised into three broad indicator categories: Weight loss or change in body state (**BWC**); Behavioural change (**BC**); Milk yield and quality (**MY**), that could potentially be measured by PLF technologies. A category relating to the environmental indicators (**Evt**) was also added (although it was not animal-based), to capture the environmental conditions in which the animals are kept (indoors and outdoors), as part of a potential risk-assessment approach to animal welfare management.

Identification of promising technologies to monitor welfare issues

An initial review of the literature on PLF technologies, including grey sources, was completed in Winter 2020-2021 in parallel to the initial welfare prioritisation (Fig. 2). A focus was the PLF technologies (animal-based or not) most frequently used for ruminants that could address welfare issues in small ruminant systems.

For the exhaustive literature search, the strategy adopted was as a multi-step and multi-actor process, including the following actions: 1) Choice of keywords to be considered to cover a wide range of welfare issues and technologies of potential interest for monitoring welfare in small ruminants. These keywords were divided into two main classes: general, such as technology, device, sensor, welfare, wellbeing, etc., and detailed such as accelerometer, GPS, parasite, mastitis, etc.; 2) General keywords were then analysed in a step-wise manner in order to maximize the papers harvested, using three search engines (Web of Science, Scopus, Direct Science) looking to find out their performance in terms of gathered papers but also in terms of putative output (preferred format excel).

To evaluate the engine coverage, a series of search trials were run using several general keywords according to the following steps: a) using one technology (e.g. sensor, GPS, accelerometer, etc.) and one care (e.g. welfare, wellbeing) keyword with "OR" as boolean (database #1); b) using keywords related to the animal species (sheep OR goats) (database #2), c) combining the above databases #1 and #2 with the boolean "AND".

Once the list of most frequently used PLF tools in the literature was established, it was refined using experts' knowledge with an expert panel to identify those that were potentially applicable for small ruminants' welfare management (Fig. 2, Step 1b). These experts (n= 18) were all animal scientists with expertise in technologies and small ruminant systems. The experts were given the opportunity to include any new PLF technologies that were not identified by the literature review. A shortlist of potential tools for each production system (dairy sheep, dairy goat, and meat sheep) was thus produced (Fig. 2).

For each production system, a short survey was then undertaken by the experts from Step 1a and Step 1b, who were asked to rank the shortlist of potential PLF tools according to their suitability or potential in measuring/assessing each of the broad categories of welfare indicators defined previously (Fig. 2, Step 3).

Results

Welfare issues prioritisation by species and production system

The prioritised issues as ranked by the stakeholders in the workshops were summed across countries within system. The frequency that each issue was ranked 'high importance' in any workshop, is presented in Tables 2-4. Inspection of the welfare prioritisations demonstrated that these tended to follow management practices rather than production purpose (Tables 2-4), and thus the most relevant welfare issues identified are presented by management system (intensive or extensive) rather than type of production (meat or milk, for sheep).

For extensively managed animals, the highest ranked welfare issues (Table 2) were associated with feed access and health, particularly chronic health conditions such as parasitism, mastitis and lameness. Behavioural and environmental issues were typically ranked lower, even though these animals were likely to be exposed to environmental extremes, such as heat or cold. The highest ranked (6^{th} most important) issue in the Behavioural Interaction domain was that of poor ewe-lamb relationships which can be a precursor to lamb mortality.

For intensively managed sheep (Table 3), the same issues of mastitis, lameness and undernutrition/malnutrition were also ranked as the most important welfare issues. However, environmental issues were considered as more important sources of welfare challenge, relating to the quality of air and bedding in particular. The most important welfare challenges relating to Behavioural Interactions were stocking density and aggression between animals when competing for limited resources.

For sheep, regardless of whether this was extensive or intensive production (Tables 2 and 3), health issues predominated as the most highly ranked welfare issues, although behavioural interactions were mentioned, they were not considered as important. For goats, however, aggression and food competition in the behavioural interaction domain was considered the most important issue (Table 4). Thereafter health (mastitis and parasitism) and undernutrition/ malnutrition were considered the most important, followed by environmental issues.

Broad categories of welfare indicators

The welfare issues and domain, their indicators and the allocated broad indicator categories are presented in Table 5 and 6, for sheep and goats, respectively.

Final list of potential technologies suitable for measuring/assessing the broad categories of welfare indicators

Table 7 presents the final list of PLF technology types and devices that could address the prioritised welfare issues by monitoring or assessing the four identified broad categories of welfare indicators (Fig. 2, Step 3).

In total, 24 technological devices (based on 12 technology types) with the potential to assess the different prioritised welfare issues were identified. Of those, only 12 devices could be considered animal-based sensors (accelerometer-based devices, proximity sensors/contact loggers, electronic milk meter; in-line milk composition sensor, respiration rate monitor, automatic weight platform linked to Radio-Frequency Identification (**RFID**), Walk-over-Weigh, weighing/sorting crate, GPS collars, RFID automatic feeder; Electronic Identification (**EID**) reader (low/high frequency RFID); EID sorting gate). The other devices were linked to the environment and/or conditions in which the animals were kept.

Discussion

For both sheep and goats, stakeholders considered that issues in all domains of welfare (Mellor et al., 2020) were important. For sheep, where two production types were considered (meat and dairy), these were not influential in the priorities placed on particular aspects of welfare, and the housing or management system (essentially indoors or outdoors) were more important. The Domains most frequently ranked as highly important for sheep were health (parasitism, mastitis, lameness, respiratory infections) and nutrition (malnutrition, undernutrition). In extensive systems, poor maternal relationships were the most highly ranked issue in the behavioural interaction domain (ranked 6th, Table 2), and the environmental Domain was generally ranked as less important than other Domains. In intensive systems, the health Domain was still considered as the most important challenge to welfare but concerns about the environment Domain (air quality, bedding and flooring) were ranked higher than for extensive systems. Behavioural interactions (stocking density and aggression/competition for food) were also highlighted (ranked 8th and 10th, Table 3). In contrast, for goat priorities, the highest ranked concern was in the behavioural interactions Domain: aggression and food competition, with other aspects of behavioural interaction (stocking density and social mixing) also ranking highly. Other highly ranked Domains for goat systems were similar to those identified in sheep (mastitis, parasitism, undernutrition).

Within each Domain there was considerably variation in the types of issues raised by the literature which would impact on the welfare of sheep and goats. For example, for sheep more than 30 specific diseases or health conditions were included in the initial assessments for the health Domain (see Supplementary Material S1), and within the nutritional Domain, impacts of insufficient feed to meet metabolic demand, poor food availability, unbalanced diets, ruminal acidosis, poisoning, and competition to access feed were all considered. However, in the stakeholder workshops often some of these were combined by stakeholders (e.g. ectoparasitism rather than specific parasites; undernutrition rather than feed availability or feed quality) and thus they have been reported in the broad categories prioritised by stakeholders, rather than the specific disease or nutritional issues originally presented. It is relevant to note, however, that each stakeholder workshop was presented with a shorter list of welfare concerns, considered by country experts to be relevant to their production systems. This may have inadvertently influenced the issues presented as relevant for welfare. For example, a poor maternal relationship was not considered in the Dairy systems, although mother-offspring separation is increasingly considered a welfare concern in cattle dairy industry (e.g. Sirovica et al., 2022).

The issues prioritised were similar to those identified in previous studies (Rioja-Lang et al., 2020; EFSA, 2014; Phythian et al., 2011; Philips et al., 2009), and reflect a generally greater prevalence of health and nutritional issues in small ruminant farming, but less concern for damaging social behaviour which can occur in other farmed systems (Rioja-Lang et al., 2020). The identification of issues with behavioural interactions (particularly aggression or agonistic behaviour in goats) suggests that these issues are still very relevant in these species and need to be considered important. However, whether the use of PLF technology can be useful for welfare management of these issues is not clear. In both species, although painful management practices were identified as important (castration in extensively managed sheep, disbudding in goats) in neither case were these ranked as highly as other issues. This seems to reflect a greater emphasis being placed by stakeholders on longer-term more chronic welfare issues, such as health and nutrition, which may appear more relevant to farm sustainability. Painful management procedures have been extensively studied in small ruminants and it may be that stakeholders believed these were not as relevant as solutions are less likely to be associated with PLF than the other prioritised welfare issues. Interestingly, and in contrast to other studies (Philips et al, 2009), stakeholders focused on welfare issues occurring on the farm, and less on those associated with transport and slaughter. This perhaps reflects the fact that regulation of animal transport and EU legislation covering this aspect of sheep and goat production has existed for the last 20 years, and thus it may have been considered less important by stakeholders.

As highlighted in Tables 5, 6 and 7, each welfare issue prioritised can result in changes in a number of measurable parameters at the individual animal level. For example, the presence of gastrointestinal parasites can cause animals to change their behaviour, becoming more lethargic, altering their feeding and drinking behaviour and their use of the landscape (e.g. Hutchings et al., 2000; Ikurior et al., 2020). Parasitised animals also experience anorexia which can result in a loss of body weight (Kyriazakis et al., 1998). Of the available technologies, behavioural change could potentially be detected via accelerometers, proximity or contact loggers, RFID readers at key resource locations (such as drinkers or feeders; e.g. Tesnière et al., 2023), use of GPS systems and drones to monitor animal movements about the landscape. Changes in body weight could be detected via systems that allow for automated weighing such as the Walk-over-Weigh or other systems. Similarly, other health conditions such as lameness or mastitis can also be associated with changes in behaviour, resource use and milk yield for dairy animals (Gougoulis et al., 2010), for which there are sensors and technology which can potentially be optimised to assess these changes.

The shortlist of potential PLF tools identified from the scientific and grey literature highlights perhaps a disconnection between promising research results, and the current actual rate of equipment use on small ruminant farms. Studies (Gautier et al., 2019; McLaren et al., 2022) have highlighted the lack of uptake by small ruminant farmers, with still very few technologies installed on farms, and the equipment already in place is mainly focused on productive traits and data such as weight and flock management (e.g. weigh crate, milk meters, EID stick readers, flock/herd software management). Individual identification of animals (with an ear-tag or a bolus) thus appears to be the basic technology on farms to ensure individual monitoring of parameters. In addition, the disparity between countries in terms of uptake of equipment and use of this mandatory tool illustrates the difficulty in deploying individual monitoring of animals with PLF. This disparity between countries can also be linked to the production system and economic return. For instance, intensive systems are more likely to invest in technology than extensive ones (Gautier et al., 2019), milk production and processing (cheese, yoghurts, etc.) can have greater economic returns than meat (Ruiz-Morales et al., 2019). The geography (East vs. West) and natural constraints will also have economic implications, as well as flock or herd size (Papanikolopoulou et al., 2023).

If barriers such as costs were removed, McLaren et al. (2022) highlighted the potential interest by small ruminant farmers to equip their farms. Equally, Sossidou et al. (2022) and Czizster et al. (2022) showed the interests by farmers of using PLF tools. For instance, in dairy sheep farms, measuring devices for milk yield (electronic milk-meter, milk tank scale) were of interest to stakeholders. Walk-over-weighing also appears to stakeholders potentially able to detect nutrition issues highlighted by frequent measurement of liveweight changes (González-García, et al., 2021; Decandia et al., 2023).

Additionally, the availability of some of the identified technological devices for everyday use on farms for welfare management is another issue. Even if all technologies listed were available on the market, none of them are tailored for welfare management. Indeed, what may make these technologies usable for welfare management are algorithms for detection of welfare issue and the associated software. For example, the offering on the market of surveillance cameras is large, however, the algorithms for automatic detection of animals and/or the characterization of their behaviours are only at the research stage. Equally, for accelerometers and proximity sensors, whilst promising tools according to the literature (Giovanetti et al., 2021), there is no routine use yet available to have alerts on variations in behaviour according to species, age, etc., or good evidence that a change in behaviour as detected by these methods can be reliably linked to a change in welfare state. Similarly, whilst the low-frequency RFID-enabled weigh-crates and readers already exist, the Walk-over-Weigh is not yet commercially available, even if though it demonstrates promising potential in monitoring weight change automatically (Leroux et al., 2023; Decandia et al., 2023). There is therefore a significant gap between the promises of technologies and their potential uses in commercial farms currently.

Another challenge for the use of these technologies for individual animal welfare management is the cost, especially for animal-based sensors. For example, GPS collars are readily available on the market, but the costs to equip every animal make them unsuitable at present for wide deployment on small ruminant farms, even though they are promising technologies to monitor individual behaviour. For these technologies, new business models would need to be defined. For instance, Kaler and Ruster (2019) argued that normalising the use of PLF technologies on sheep farms would benefit from manufacturers/suppliers being able to understand how farmers interpret the value of technology, and to co-design and work with them to ensure technology is seen as an aid to good stockmanship rather than a mechanism for profit maximisation. Conversely, non-animal-based sensor technologies, such as sensors to monitor shed conditions, are not expensive but only provide global information about the environmental conditions to which the animals are exposed, and do not allow individual animal monitoring. From this perspective, we can deduce that most of welfare priorities and indicators will be difficult to study directly using PLF. In fact, most of the PLF tools identified in this study as potential for monitoring individual behavioural changes may be difficult to be used on a wide range of sheep and goat farms, due to low TRL (algorithm and software) or high costs.

An alternative to animal-based sensors, or by extension those that can monitor the animal individually, for welfare management is to incorporate a risk-management approach to welfare. Although some aspects of environmental stress can be assessed through animal indicators (e.g. heat stress through panting or increased water use; bedding cleanliness through fleece cleanliness; etc.), it is also possible to incorporate additional information through the use of PLF in environmental sensing. This has the advantage of having greater TRL than animal-based sensors and can be considerably cheaper than individual animal assessment. The disadvantage of this approach is that it does not provide the level of individual animal monitoring that can be a key component of the use of PLF and is usually considered 'gold standard' for welfare assessment but could provide an early warning system for the potential risks of animal welfare compromise and alert farmers to the need to implement mitigation actions.

Conclusions

This paper presents results from two literature searches, as well as advice and opinions of stakeholders and experts on welfare issues and technologies for small ruminant production systems, which led to the prioritisation of welfare issues and potential PLF tools or devices that could help their management. This exploration of the use of PLF to assist small ruminant welfare management is unique, and in its infancy in terms of application. Although many PLF tools could be promising for welfare management, most of them are not specific enough or yet suitable for small ruminant systems. They may however provide a global alert communicating that 'something is wrong', whereas the exact issue would still need to be verified by the farmer. In future and currently ongoing works, the most promising PLF tools should be tested and validated on experimental and commercial farms, and their potential applicability for welfare management assessed under a large spectrum of conditions.

Ethics approval

The workshops were subject to human participation ethics rules, as described in the TechCare project (D9.1 H requirement No.1 – Human) and the participants and results anonymisation followed the GDPR rules as described in the TechCare project (D9.2 – PODP requirement No.2 – Protection of Personal Data). The disclaimer and attendance sheets distributed and completed during the workshops constituted the ethics agreement.

Data and model availability statement

None of the data were deposited in an official repository. The PLF literature review is stored online in two private groups on the Mendeley database. These data are available to reviewers or available from the authors upon request. It is envisaged that the data presented in this work will be made publicly available on the TechCare' Zenodo site (https://zenodo.org/communities/techcare/about)

Declaration of Generative AI and AI-assisted technologies in the writing process,

No Generative AI and no AI-assisted technologies have been used in the writing process

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Declaration of interest,

None

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Table 1

Stakeholders' workshops in each country, production system (dairy sheep, dairy goats or meat sheep) with the number of participants and their category.

Country	Production system considered	No. of participants (and category)
France	Dairy & Meat sheep, Dairy & Meat lambs	68 (15 farmers; 11 researchers, 5 lecturers, 20 advisors, 17 value chain)
Greece	Dairy sheep & Dairy goats	18 (12 farmers, 4 vets, 1 researcher, 1 value chain)
Ireland	Meat sheep	18 (8 farmers, 2 researchers, 4 advisors, 1 vet, 3 value chain)
Israel	Meat sheep	4 (2 farmers, 2 researchers)
Italy	Dairy sheep	26 (10 farmers, 3 researchers, 8 advisors, 5 value chain)
Norway	Dairy goats & Meat sheep	18 (9 farmers, 3 researchers, 4 advisors, 1 lecturer, 1 vet)
Romania	Dairy sheep	30 (19 farmers, 7 researchers, 4 advisors)
Spain	Meat & Dairy sheep; Meat & Dairy lambs; Dairy goats	47 (5 farmers, 10 vets, 22 researchers, 10 advisors)
United Kingdom	Meat sheep	25 (11 farmers; 1 researcher, 1 lecturer, 7 advisors, 4 value chain, 1 welfare organisation)

Table 2

Sheep welfare issues (and domain) priorities identified and ranked by the stakeholders for extensive systems.

Welfare Domain	Welfare Issue	Summed priority (times cited/no. workshops)[1]	Number highest ranks/no. workshop[2]
Health	Gastro-intestinal parasites	1.0	5/6
Nutrition	Undernutrition/malnutrition	1.0	4/6
Health	Lameness	1.0	4/6
Health	Mastitis	0.83	3/6
Health	Ectoparasites	0.83	2/6
Behavioural interactions	Poor maternal relationships	0.66	1/6
Health	Morbidity/mortality	0.5	3/6
Nutrition	Inadequate water quality	0.5	0/6
Health	Reproductive disorders	0.5	0/6
Health	Respiratory infection	0.33	1/6
Behavioural interaction	Predation/dog worrying	0.33	0/6
Environment	Environmental stress	0.33	0/6
Behavioural interactions	Lost on the range	0.17	1/6

Behavioural interactions	Rough handling	0.17	0/6
Health	Castration	0.17	0/6
Environment	Heat stress	0.17	0/6
Behavioural interactions	Stocking density	0.17	0/6
Environment	Lack of shade/shelter	0.17	0/6

[1] number of times the issue was cited in the workshops divided by the number of workshops

[2]number of times the issue was ranked highest in the workshops, divided by the number of workshops

Table 3

Sheep welfare issues (and domain) priorities identified and ranked by the stakeholders for intensive systems.

Welfare Domain	Welfare Issue	Summed priority (times cited/no. workshops)[1]	Number highest ranks/no. workshop[2]
Health	Mastitis	0.71	4/7
Nutrition	Undernutrition/malnutrition	0.71	2/7
Health	Lameness	0.57	2/7
Health	Respiratory infection	0.57	2/7
Health	Gastrointestinal parasites	0.57	2/7
Environment	Quality and cleanliness of flooring/bedding	0.57	1/7
Environment	Poor air quality	0.43	2/7
Behavioural interactions	Stocking density	0.43	1/7
Health	Reproductive disorders (e.g. abortion, dystocia)	0.43	1/7
Behavioural interactions	Competition/aggression	0.29	2/7
Nutrition	Inadequate water quality	0.29	1/7
Environment	Poor quality housing	0.29	1/7

Environment	Heat stress	0.29	0/7
Health	Ectoparasites	0.14	1/7
Behavioural interactions	Rough handling	0.14	0/7
Behavioural interactions	Poor maternal relationships	0.14	0/7

[1]number of times the issue was cited in the workshops divided by the number of workshops

[2]number of times the issue was ranked highest in the workshops, divided by the number of workshops

Table 4

Goat welfare issues (and domain) priorities identified and ranked by the stakeholders

Welfare Domain	Welfare Issue	Summed priority (times cited/no. workshops)[1]	Number highest ranks/no. workshop[2]
Behavioural interactions	Aggression/food competition	1.0	2/2
Health	Mastitis	1.0	1/2
Health	Gastrointestinal parasites	1.0	1/2
Health	Ectoparasites	1.0	1/2
Nutrition	Undernutrition/malnutrition	1.0	1/2
Environment	Quality and cleanliness of flooring/bedding	0.5	1/2
Behavioural interactions	Stocking density	0.5	1/2
Behavioural interactions	Social mixing	0.5	1/2
Health	Lameness	0.5	0/2
Health	Disbudding	0.5	0/2
Health	Dystocia	0.5	0/2
Behavioural interactions	Stereotypic behaviour	0.5	0/2
Health	Morbidity/mortality	0.5	0/2
Health	Losses from accident	0.5	0/2

[1]number of times the issue was cited in the workshops divided by the number of workshops

[2]number of times the issue was ranked highest in the workshops, divided by the number of workshops

Table 5

List of prioritised welfare issues (and domain) for sheep, their corresponding indicators and their allocated broad welfare indicators categories

Welfare Domain	Welfare issues	Welfare indicators[1]	Broad indicator category
Nutrition	Undernutrition/ Malnutrition	Body Condition Score, queuing at feeders, weight loss, metabolic disease, reduced milk yield, milk fatty acid composition, milk protein, milk urea, behaviour (work to access feed; stereotypic behaviour e.g. wool biting)	Weight loss or change in body state; Behavioural change; Milk yield and quality
Health	Mastitis	Behaviour (apathy, reduced feed intake), facial expression, fever, udder shape and colour, milk yield, somatic cell count	Behavioural change; Milk yield and quality
Health	Gastrointestinal parasites	Diarrhoea, reduced feed intake, loss of weight/growth, death	Weight loss or change in body state; Behavioural change
Health	Lameness	Gait scoring, grazing/feeding on knees, Body Condition Score, head nodding, spinal curvature	Weight loss or change in body state; Behavioural change
Health	Ectoparasites	Behaviour: (rubbing, scratching, head roll); lesions, fitting, coat condition, apathy, clinical examination, faecal soiling (predisposition)	Behavioural change
Nutrition	Inadequate water supply	Queuing at drinkers, loss of Body Condition Score, reduced milk yield, apathy.	Weight loss or change in body state; Behavioural change; Milk yield and quality

Environment	Inappropriate housing	Frequency and duration of lying behaviour; dirty coat; coat condition, mastitis, lameness; Respiratory distress, nasal discharge; Environmental indicators: assessment of air quality, humidity and bedding measures	Behavioural change; Environmental indicators

[1]From the literature. See Supplementary Material S1.

Table 6

List of prioritised welfare issues (and domain) for goats, their corresponding indicators and their allocated broad welfare indicators categories

Welfare Domain	Welfare issues	Welfare indicators[1]	Broad indicator category
Health	Mastitis	Clinical exam, bacterial culture, udder shape, sickness behaviour (apathy, reduced feed intake), fever	Behavioural change; Milk yield and quality
Nutrition	Insufficient food and water	Queuing at feeders & drinkers	Behavioural change
Behavioural Interactions	Agonistic behaviour/feed competition	Queuing at feed face, Behaviour	Behavioural change
Environment	Poor environmental management	Behaviour (lying preferences, lying behaviour); udder cleanliness, coat cleanliness, Qualitative Behaviour Assessment, knee and hock calluses, dirty coat, ocular discharge, coughing + environmental indicators: measures of bedding humidity and cleanliness	Behavioural change; Environmental indicators
Health	Gastrointestinal parasites	Diarrhoea, reduced feed intake, loss of weight/growth, death	Weight loss or change in body state; Behavioural change
Health	Ectoparasites	Scratching, coat condition	Behavioural change
Health	Lameness/claw health	Clinical exam, hoof shape assessment, walking ability, gait scoring	Behavioural change

[1]From the literature. See Supplementary Material S1.

Table 7

Final list of potential technologies and their capacity to monitor or measure the broad welfare indicator categories by prioritised welfare issues and domain, for dairy sheep, dairy goats and meat sheep

		Prioritised welfare issue (and domain)								
		Nutrition	Health	Health	Health	Health	Nutrition	Environment	Behavioural Interactions	Environment
Technology type	Technological devices	Nutritional issues (under /malnutrition)	Mastitis	Gastrointestinal parasites	Lameness/claw health	Ectoparasites	Inadequate water supply	Inappropriate housing	Agonistic behaviour/feed competition	Poor environmental management
Acceleration detection	Accelerometer-based devices (+/- geolocation)	BC	BC			BC		BC	BC	BC
Electromagnetic waves	Proximity sensors/Contact logger	BWC		BWC	BWC		BWC			
Flow meter	Water meter	BC		BC	BC		BC			

Flow/Pressure sensor	Milk measurement (Electronic milk meter, In-line composition sensor, Bulk tank scales)	MY	MY							
Gas detection	Ammonia sensors							Evt		Evt
Micro-sonic waves	Automatic grass height measurement devices	BWC		BWC	BWC		BWC			
Pressure sensor	Automated Liveweight scales (Automatic weight platform linked to RFID[1], Walk-over-Weigh, Weighing[2]/sorting crate)	BWC		BWC	BWC		BWC			
Pressure or temperature sensor	Respiration rate monitor	BC	BC	BC	BC	BC	BC	BC; Evt	BC	BC; Evt

Radio Frequency ID reader	RFID-based devices (Automatic feeder; EID reader (low/high frequency RFID); EID Sorting gate)	BWC; BC		BWC; BC	BWC; BC		BWC; BC			
Radio navigation system	Global Positioning System collars	BC	BC	BC	BC	BC	BC	BC	BC	BC
Temperature and/or humidity sensor	Temperature, humidity and black globe temperature sensors							Evt		Evt
Thermography	Infrared thermography camera	MY	MY				MY			
Thermography /gas detection	Weather station							Evt		Evt
Vision sensor	Video devices (Unmanned Aerial Vehicle video/ Drone; camera)	BC	BC	BC	BC	BC		BC	BC	BC

Abbreviations: RFID=Radio Frequency Identification; EID=Electronic Identification BWC = Body Weight Change; BC = Behaviour Change; MY = Milk Yield and composition; Evt = Environmental indicators

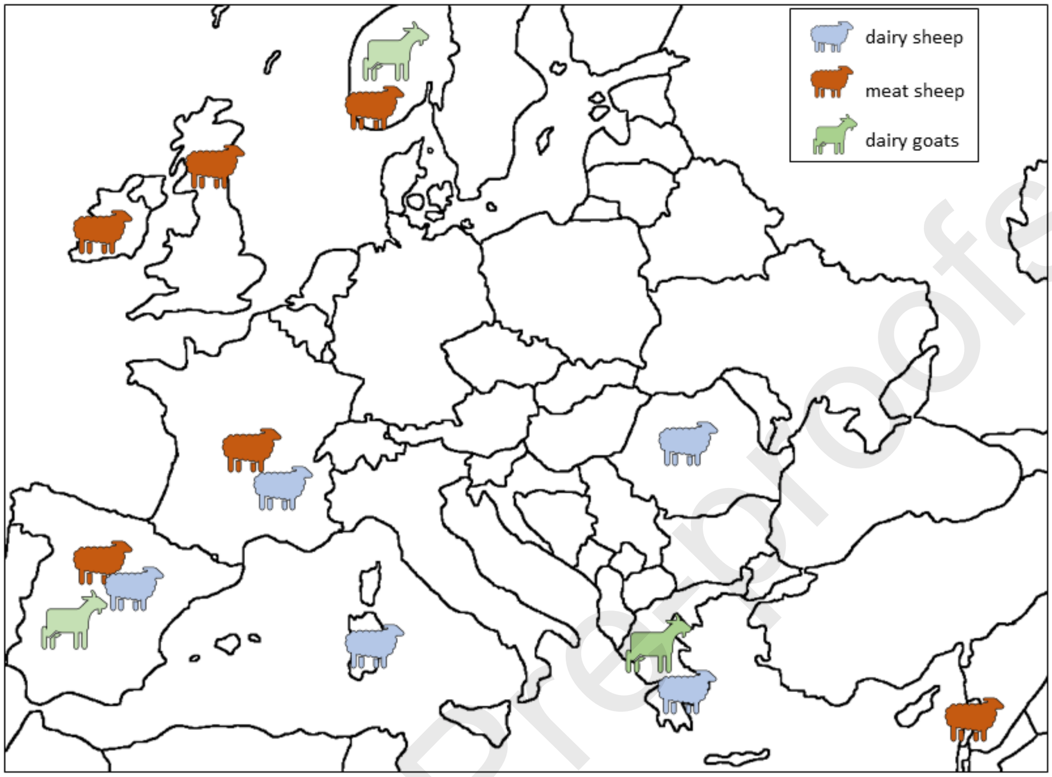
[1] static scale

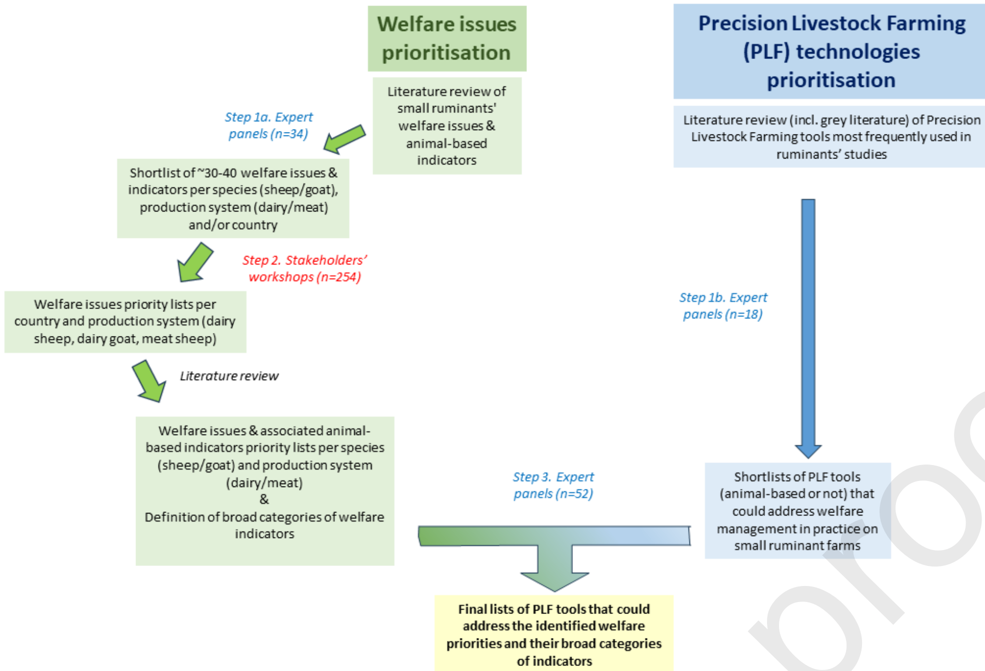
[2] dynamic scale

List of figure captions

Figure 1. Countries and small ruminant production systems involved in the study

Figure 2. Schematic representation of the study's methodological approach to explore the use of Precision Livestock Farming for small ruminant welfare management


dairy sheep
meat sheep
dairy goats



Welfare issues prioritisation
Literature review of small ruminants' welfare issues & animal-based indicators
Step 1a. Expert panels (n=34)
Shortlist of ~30-40 welfare issues & indicators per species (sheep/goat), production system (dairy/meat) and/or country
Step 2. Stakeholders' workshops (n=254)
Welfare issues priority lists per country and production system (dairy sheep, dairy goat, meat sheep)
Literature review
Welfare issues & associated animal-based indicators priority lists per species (sheep/goat) and production system (dairy/meat) & Definition of broad categories of welfare indicators
Precision Livestock Farming (PLF) technologies prioritisation
Literature review (incl. grey literature) of Precision Livestock Farming tools most frequently used in ruminants' studies
Step 1b. Expert panels (n=18)
Shortlists of PLF tools (animal-based or not) that could address welfare management in practice on small ruminant farms
Step 3. Expert panels (n=52)
Final lists of PLF tools that could address the identified welfare priorities and their broad categories of indicators

Author contributions

Author contributions,

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