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Review: Precision Livestock Farming technologies in pasture-based livestock systems

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ABSTRACT

Precision Livestock Farming (**PLF**) encompasses the combined application of single technologies or multiple tools in integrated systems for real-time and individual monitoring of livestock. In grazing systems, some PLF applications could substantially improve farmers' control of livestock by overcoming issues related to pasture utilisation and management, and animal monitoring and control. A focused literature review was carried out to identify technologies already applied or at an advanced stage of development for livestock management in pastures, specifically cattle, sheep, goats, pigs, poultry. Applications of PLF in pasture-based systems were examined for cattle, sheep, goats, pigs, and poultry. The earliest technology applied to livestock was the radio frequency identification tag, allowing the identification of individuals, but also for retrieving important information such as maternal pedigree. Walk-over-weigh platforms were used to record individual and flock weights. Coupled with automatic drafting systems, they were tested to divide the animals according to their needs. Few studies have dealt with remote body temperature assessment, although the use of thermography is spreading to monitor both intensively reared and wild animals. Global positioning system and accelerometers are among the most applied technologies, with several solutions available on the market. These tools are used for several purposes, such as animal location, theft prevention, assessment of activity budget, behaviour, and feed intake of grazing animals, as well as for reproduction monitoring (i.e., oestrus, calving, or lambing). Remote sensing by satellite images or unmanned aerial vehicles (**UAVs**) seems promising for biomass assessment and herd management based on pasture availability, and some attempts to use UAVs to monitor, track, or even muster animals have been reported recently. Virtual fencing is among the upcoming technologies aimed at grazing management. This system allows the management of animals at pasture without physical fences but relies on associative learning between audio cues and an electric shock delivered if the animal does not change direction after the acoustic warning. Regardless of the different technologies applied, some common constraints have been reported on the application of PLF in grazing systems, especially when compared with indoor or confined livestock systems. Battery lifespan, transmission range, service coverage, storage capacity, and economic affordability were the main factors. However, even if the awareness of the existence and the potential of these upcoming tools are still limited, farmers' and researchers' demands are increasing, and positive outcomes in terms of rangeland conservation, animal welfare, and labour optimisation are expected from the spread of PLF in grazing systems.

Implications

New technologies help farmers to improve animal welfare and management, and to deepen understanding of animal behaviours. They are already applied in intensive rearing systems but could also be useful in pasture-based systems, where livestock control can be difficult owing to their physical scale, variability, and density of the feed base and remoteness. Raising awareness of available technological solutions for extensive farming conditions could enhance the adoption among farmers and researchers. Increasing their use in grazing systems could be also beneficial for animal welfare and rangeland conservation, as well as supporting farmers in decision-making, reducing workload, and increasing profits.

Introduction

Precision Livestock Farming (**PLF**) is defined as "individual animal management by continuous real-time monitoring of health,

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welfare, production/reproduction, and environmental impact" (Berckmans, 2017). PLF includes the combined application of single or multiple tools in integrated systems. This has been made possible by technological developments over the last 20 years in fields such as information and communication technologies, internet of things, wireless communication networks, and Internet access availability (Terrasson et al., 2017). Advances in engineering and biomaterials research, which have led to the miniaturisation of electronic devices and decreased cost of electronics, have also been pivotal drivers for the diffusion of PLF (Neethirajan et al., 2017). PLF could provide farmers with continuous, non-intrusive, and objective data collection, able to detect small but significant changes in behavioural patterns or apparently unrelated parameters, which greatly improve farmers' decision management (Frost et al., 1997). In pasture-based systems, this type of support for farmers is very important considering that farmer's control on animal is less frequent.

In the last decades, the PLF sector has rapidly evolved, from its earlier applications for electronic milk meters to novel wearable sensors and integrated systems capable of detecting an animal's physiological and reproductive status with acceptable reliability through behaviour analysis, rumination monitoring, and online real-time data harvesting (Halachmi et al., 2019). The information collected is elaborated and made available to end-users on smartphones and laptops, enabling farmers to put in practice better management of one or more production inputs or to identify and intervene before the onset of clinical illness (Andonovic et al., 2018). Currently, PLF is mainly developed for intensive farming systems, especially indoors, where farm structures and facilities are well suited for the needs of present digitisation (limited space, control of environmental conditions, easy access to electricity, and information and communication technologies). However, PLF could also be very useful in pasture-based systems, especially during seasonal grazing, when farmers' control of livestock can be difficult owing to the physical scale of pasture-based systems, variability, and density of the feed base and remoteness.

The application of PLF to livestock systems has already been reviewed by several authors (Neethirajan, 2017; Neethirajan et al., 2017; Halachmi et al., 2019), without regard to the rearing systems where the devices were applied. A focus on pasture-based/extensive livestock systems was addressed by Handcock et al. (2009), González et al. (2014), and Bailey et al. (2021) who examined the use of PLF technologies to monitor cattle behaviour and management at pasture. Odintsov Vaintrub et al. (2021) and Fogarty et al. (2018) reviewed the application of PLF in sheep farming. Recently, Herlin et al. (2021) examined the use of digital tools to assess animal welfare in grazing cattle and sheep.

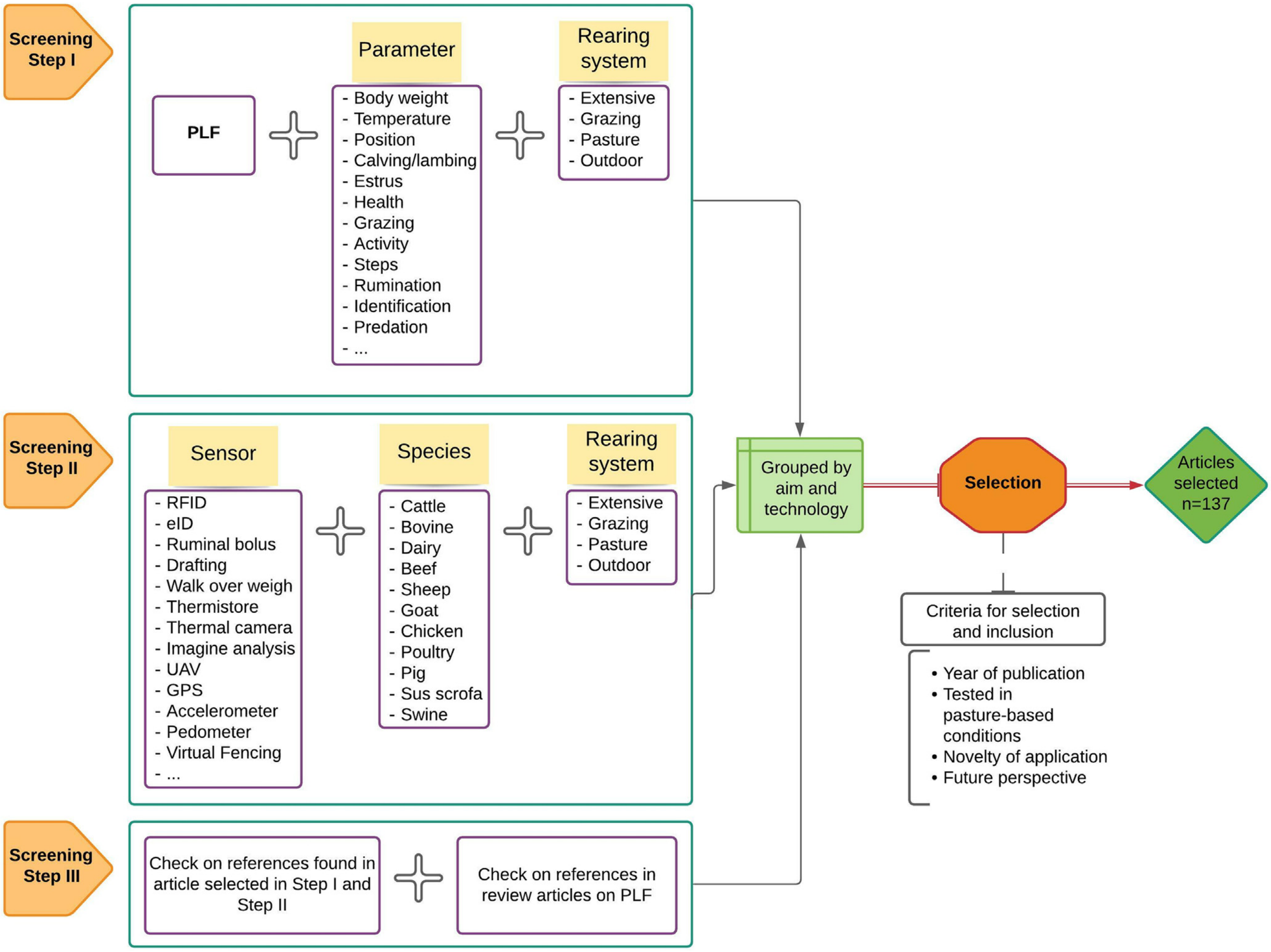

Fig. 1. Scheme of the literature searching process based on keywords related to the parameter of interest (e.g., BW, Temperature, position, activity, health, etc.), rearing system, sensor (e.g., accelerometer, global positioning systems, virtual fencing, etc.), species (e.g., cattle, sheep, goat, poultry, pig, etc.), and the following selection process according to chosen selection criteria (e.g., year of publication, testing conditions, novelty, development state). Abbreviations: PLF = precision livestock farming; RFID = radiofrequency identification; eID = electronic identification; UAV = unmanned aerial vehicle; GPS = global positioning system.

The present work aimed to provide a focused review on the available PLF technologies for livestock on pasture-based systems, as well as to identify the main hurdles to further adoption of PLF applications in these systems.

Material and methods

Screening

An extensive literature screening, as shown in Fig. 1, was performed to evaluate the state of the art application of PLF in pasture-based farming systems. The search was conducted on Google Scholar® and Scopus® databases, without any limits on the date, country, or climate.

Three consecutive approaches were used to carry out the screening process:

(i) use of combined keywords, such as “PLF” AND parameter of interest (e.g., temperature, BW, virtual fencing, etc.) AND “extensive” OR “grazing” OR “pasture”;
(ii) use of the specific PLF technology as keyword (e.g., Global positioning system (**GPS**), accelerometer, etc.) AND the animal species (“cattle,” “bovine,” “sheep,” “goat,” “beef,” “dairy,” “pig,” “swine,” “*Sus scrofa*,” “chicken,” “poultry”);
(iii) examination of the references reported both in the reviews on PLF and in the articles selected in steps (i) and (ii). This third screening phase was carried out to check whether additional articles were considered suitable for the chosen topic.

Selection

After the screening phase, articles were grouped according to the technologies used and the objective of each PLF application (e.g., GPS for location, tracking, or behavioural studies; accelerometers for health monitoring, oestrus detection, etc.). This grouping established the main structure of the present work, as described in Section 3.

Among the articles resulting from the screening phase, an initial selection was performed by examining every Material and Methods section. This phase was mainly aimed at ensuring that the PLF technologies reported were actually applied in pasture-based systems, and the devices were tested under field conditions. Then, the remaining articles were examined in greater depth to identify the ones most representative of each selected technology. Since the objective of the present work was to perform a focused literature review, a further and final selection step was carried out using the publication year as the preferential criterion to choose the most recent studies between similar ones, especially for those technologies that are more widespread, such as GPS.

A summary of the articles selected for the type of device and animal species is presented in Table 1.

Table 1
Number of selected articles according to species and tool location.

Species	On-animal tools	Off-animal tools
Cattle	43	21
Sheep	24	8
Goats	3	1
Buffalos		1
Pigs	2	1
Chickens	2	

Precision Livestock Farming applications in pasture-based systems

The applications of PLF in pasture-based systems were reviewed, considering both precommercial research technologies and commercial solutions. PLF technologies were organised according to the aim for which they were used and the parameters they assessed. Some are already used in intensive livestock systems but have also been applied in pasture-based systems, while others are specifically thought to address specific issues related to pasture-based systems. The variable development stages were also noted. Some devices developed for scientific research were also reported because of their indirect contribution to outlining novel management practices with effective applications in rangelands.

Animal identification

Several animal identification methods are used, some of which rely on technologies already available on the market or at the final development stages, as recently reviewed by Awad (2016). According to the classification performed by Awad (2016), classical cattle identification systems were grouped into permanent methods (ear notching, ear tattooing, hot iron, or freeze branding), temporary methods (ear tagging with plastic or metal tags), and electronic methods. Electrical methods mainly consist of radio frequency identification tags (**RFID**) and can be grouped into boluses, ear tags, and injectable glass tags. The tag on the animal transmits the information by radiofrequency to the tag reader; usually, this is the only part of the system that requires an external power source. RFID offers an easy and affordable way to identify, track, and monitor livestock, thus improving the traceability of animals along the supply chain (Ruiz-Garcia and Lunadei, 2011). The adoption of RFID technology in practical farm management has allowed the development of managerial software where daily records on individuals (e.g., medical treatments, growth performance, pedigree, reproductive performance, etc.) are automatically stored (Ruiz-Garcia and Lunadei, 2011). The most widespread is the electronic ear tag, which is widely used in grazing systems and is a mandatory identification system in some countries. The endo-ruminal bolus is less widely used (Rutter, 2017). Compared to RFID ear tags, injectable RFID tags offer a high level of reliability and security and are difficult to remove, modify, or lose (Carné et al., 2009). However, this also means that transponder recovery can be difficult along the supply chain (Awad, 2016). In addition, in crowded conditions, such as in cows in the milking parlour, Štoković et al. (2009) observed reading failure using an endo-ruminal bolus, whereas Pinna et al. (2006) reported 100% readability in static conditions (restrained animals) using a hand-held tag reader. Lately, also smart ear tag embedded with accelerometer to detect several parameters related to animal welfare and reproductive performances are available on market (e.g. Allflex SenseHub®, SCR Engineers Ltd.). They can also be used to identify the individuals, but their recognition as an official identification system depends on countries.

Body weight

Accurate measurement of BW is important for livestock management at pasture; indeed, i.e. it is critical for determining stocking rates. As reported by Wangchuk et al. (2018), though the weighing scale is the gold standard for obtaining direct measures, it is time-consuming and stressful for animals; additionally, its use is not always easy depending on farm facilities and animal location (e.g., for animals kept in seasonal pastures). Wangchuk et al. (2018)

reported several techniques for estimating the BW of livestock, starting from linear body measurements. These are less accurate than weighing scales and do not address the issue of individual animal handling.

To overcome these problems, platforms known as ''Walk-over-Weigh" (**WOW**) have been developed and applied in the dairy industry (Brown et al., 2015). However, they have become an option in pasture-based systems where animals remain for weeks or even months without being handled. Some improvements made in recent years, such as solar-powered batteries and data transmission systems, have allowed their use in rangelands for sheep and cattle. The WOW consists of a specially designed crate on which the animal walks, allowing the body mass to be estimated using continuous averaging techniques (González-García et al., 2018). They can also be equipped with a tag reader to automatically identify the animal being weighed.

The WOW is usually placed at a restricted entry point for an attractant (e.g., feed, water) so that when the animal enters, it is weighed and identified. Growth rates can then be calculated and used as prediction tools to monitor the condition of the animals, for example, for the early detection of pasture-borne nematode infections (Segerkvist et al., 2020), as well as to open new pasture areas when scarcity of resources start affecting the growth.

Automated data harvesting reduces stress on animals (with no handling necessary) and labour. However, raw data need to be checked, manually or by software, to delete inaccurate records that might be generated. Bad data can also be produced if, for example, the animal is running, if more than one animal stands on the scale at once, or if animals stand with only two legs on the platform (Brown et al., 2015). Recently, attention has been focused on problems related to repeatability and data accumulation. Brown et al. (2014) reported that at least 3 weeks were required to obtain the 12 consecutive individual records required to estimate live weight. Repeatability found by Simanungkalit et al. (2020) in grazing cattle was slightly higher than that found by Brown et al. (2014); however, at least five to ten individual measurements were needed to reach consistent weight records. González-García et al. (2018) suggested that, by providing 2–3 weeks of adaptation and using a 'flow-control' device (S module), would be possible to overcome most of the problems reported in former studies. However, the time needed for the system to 'learn' each animal remains an issue for rapid decision-making. A WOW system without a tag reader but coupled with a device for data storage was used for overall live weight assessment (Brown et al., 2012). In this case, an average of 5 days was enough to estimate flock weight with 95% confidence intervals of less than 2 kg, and was also cheaper and simpler than a WOW linked to individual identification.

Differences in consecutive live weight measures were used by Aldridge et al. (2017) and Menzies et al. (2018a) to identify the postpartum anoestrus interval of grazing cattle, thus enhancing reproductive efficiency and supporting genetic selection. Menzies et al. (2018a) concluded that this application of WOW was promising, but further research was required for the 10 days of accuracy obtained on the parturition date to be sufficiently reliable for genetic programmes.

Image analysis based on 2D and 3D sensors is gaining attention to estimate body condition scores, BW, and morphometric evaluations. This would provide farmers with contactless, automated, real-time, and continuous detection of two parameters of pivotal importance for breeding, animal welfare (Qiao et al., 2021; Kamchen et al., 2021), and to determine when the animal has reached the market's requirements for slaughtering. However, these techniques have, to date, been tested mainly in indoor systems, most likely because of the need for optimal and constant environmental conditions to obtain animal contours, as well as animal motion and position in front of the sensor to extract useful features reliably (Qiao et al., 2021). For pigs, Ymaging® (Spain) (see Table 2) has recently developed a portable device called PigWei to estimate pig live weight both indoors and outdoors; it offers a specific customisation for Iberian pigs reared both indoors and outdoors.

Automatic drafting systems

Automatic drafting systems generally rely on the combined use of other PLF devices, such as WOW and/or RFID. Farms endowed with automatic drafting gates can divide animals in the herd according to the features of interest. For instance, animals that have reached the slaughtering weight, or females close to parturition, newborn lambs or calves, animals that need feed supplementation or medical treatments can be allocated to different spaces (Morgan-Davies et al., 2018; DataMuster®, Patent 2005233651 owned by Sheep CRC Ltd see Table 2).

Temperature

In indoor systems, environmental temperature and humidity were the first parameters monitored by online devices. These parameters are used to calculate the temperature and humidity index (**THI**), which evaluates the level of thermal stress in a given environment (Renaudeau et al., 2012). THI scores are used to quickly intervene before the animals enter heat stress. In rangelands, animals are free to move towards shelters and tree-covered areas to self-regulate their temperature. However, self-regulation is not always possible, for example, in arid and semi-arid rangelands, as well as in tropical climates, where tree coverage might be insufficient to control heat stress. Therefore, the monitoring of environmental parameters and THI could be very useful during grazing and could support farmers in herd management according to pasture features (e.g., tree patterns) (Pezzopane et al., 2019).

In addition to heat stress evaluation, body temperature reflects the physiological activity of the animal body and, for this reason, reflects the health status of animals (Zhang et al., 2019). Rectal temperature is usually the most common and accurate method, but manual measurement is time-consuming and labour-intensive, and can cause intense stress to the animal, affecting its reliability (Zhang et al., 2019). To overcome these issues, other types of measuring devices have been developed, such as surgically implanted devices, infrared devices, and endo-ruminal boluses equipped with temperature sensors (e.g., smaXtec GmbH).

Surgically implanted devices have been used to monitor the body temperature and heart rate of domestic sheep that freely range on unfenced mountain pastures (Fuchs et al., 2019). When integrated into a monitor system capable of online data transmission, these could be a feasible method for real-time monitoring of body temperature during grazing.

Alternatively, infrared off-animal devices can also be used. Despite recent implementations of infrared technology in agriculture in general and in livestock, its use for real-time monitoring in outdoor conditions has not yet been reported. However, in free-range grazing animals, the advantage of not necessitating capture is counterbalanced by factors that affect the accuracy and reliability of the measurement. Sensors and devices should be calibrated with a known standard of thermometry, considering changes in meteorological parameters between measurements which can impact the quality of the transmission of infrared waves emitted by the animal as well as the quality of the reception of the waves (Sellier et al., 2014). Moreover, it is important that the body surface to be analysed is clean, because dirty or wet coats may modify the emissivity (McManus et al., 2016). The resolution of

Table 2
Main systems on the market consisting of combined sensors to monitor and manage livestock.

Name	Species	Sensors	Outputs[1]	Country	Website (accessed on 13 July 2021)
Pigwei®, Ymaging	Pig	Imagine analysis	Live weight	Spain	http://www.ymaging.com/projects-2/pigwei
Datamuster®	Cattle	Walk-over-weigh (weighing crate)	Maternal parentage, reproductive efficiency, growth rates, calving, property mapping	Australia	https://www.datamuster.net.au/
smaXtec®, GmbH	Cattle	Accelerometer, thermometer	pH, body temperature, calving, heat, health, rumination	Austria, Germany	https://smaxtec.com/en/
Ceres Tag®, CeresTag Pty Ltd	Cattle	GPS, Accelerometer	Activity, Geofencing, health	Australia	https://www.cerestag.com/
digitanimal®	Cattle, horses, sheep, goats	GPS, Accelerometer, thermometer	Activity, Geofencing, body temperature	Spain	https://digitanimal.com/?lang=en
Allflex SenseHub®, SCR Engineers Ltd.	Cattle	Accelerometer	Health, rumination, intake, heat, calving, activity, heat stress	Israel	https://www.allflex.global/livestock-monitoring/
Moomonitor+®, Dairymaster	Cattle	Accelerometer	Activity, resting, feeding, rumination, heat detection	Ireland	https://www.dairymaster.com/products/moomonitor/
IceTag® and IceQube®, IceRobotics, Ltd	Cattle	Accelerometer	Lameness, activity, resting, heat detection	UK	https://www.icerobotics.com/
Moocall®	Cattle	Accelerometer	Calving, heat detection	Ireland	https://www.moocall.com/
CalveSense®, SCR Engineers Ltd.	Cattle	Accelerometer	Calving	Israel	https://www.allflex.global/livestock-monitoring/
eShepherd®, Agersens	Cattle	GPS, accelerometer	Virtual fencing, activity monitoring, pasture management	Australia	https://agersens.com/
Halter®	Cattle	GPS, accelerometer	Virtual fencing, activity monitoring, pasture management	New Zealand	https://halterhq.com/
Vence®	Cattle	GPS, accelerometer	Virtual fencing, activity monitoring, pasture management	USA	http://vence.io/
Nofence®	Cattle, sheep, goats	GPS, accelerometer	Virtual fencing, activity monitoring	Norway	https://www.nofence.no/en

Abbreviations: GPS = Global Positioning System.
[1] Functionalities as reported on the website of the seller.

the equipment, as well as the distance at which the measurement was carried out, is also fundamental for a successful analysis.

In free-range grazing livestock, research using infrared thermography has been applied to evaluate the effects of tree shading on the behaviour and body surface temperatures of beef cattle in a tropical climate (Giro et al., 2019), and to evaluate the thermoregulatory response of female buffalos raised in a tropical climate (Brcko et al., 2020). However, it could also be a practical method to realise quick assessments of suspicious health issues or to monitor the herd health status during routine checks, even in animals at pasture.

In addition, unmanned aerial vehicles (**UAV**s) have been proposed for detecting temperature data emitted from ear tags in cattle and for counting cattle through visual analysis (Chamoso et al., 2014; Barbedo et al., 2020; Shao et al., 2020; Xu et al., 2020).

Animal location and prevention of livestock theft

GPS devices have been used to prevent cattle theft in several parts of the world. In an Italian study, where a GPS collar was coupled with the global system for mobile communication (**GSM**), animals were tracked using software that alerted the farmer when an animal moved outside its grazing area, denoted by a virtual perimeter (Tangorra et al., 2013). Despite the interesting implications for farmers, an important hurdle to on-farm extensive use of GPS-embedded devices is the high cost of this technology; providing each livestock unit with a GPS tracker is often economically unaffordable for most farmers. Therefore, attempts have been made to reduce the unit cost. For instance, Karl and Sprinkle (2019) tested low-cost collars ($54) built using commercial off-the-shelf electronic components. However, apart from their economic convenience and easy handling, the collars were characterised by several limitations compared with commercial devices, such as limited battery duration (weeks) and lack of wireless data transmission. To overcome wireless data transmission and financial cost constraints of tracking solutions based on GPS, Maroto-Molina et al. (2019) developed and tested under farm conditions a low-cost solution that required only some animals of the herd being fitted with GPS collars connected to a Sigfox network and the rest with low-cost Bluetooth tags.

Another important factor limiting the use of GPS-embedded devices for herd location is the battery lifespan. In rangelands, animal handling is reduced to a minimum with manual interventions spread over long periods of time. Efficient tracking systems should cover the entire grazing season while avoiding or minimising battery changes. This issue has gradually been overcoming by the implementation of solar panels embedded to the devices. A network architecture of herd localisation with most of its nodes kinetically powered from animal movements was successfully tested to track and localise Scandinavian reindeer herds in Lapland (Dopico et al., 2012).

GPS locators have also been used in combination with other tools such as accelerometers and temperature sensors (e.g., Ceres tag®, digitanimal®, see Table 2) to monitor animal activity and health. Another emerging use of GPS is virtual fencing, which will be discussed in Section 3.7.

To overcome accuracy-related problems, such as loss of satellite reception owing to atmospheric conditions, topography, canopy and near infrastructure, or satellite-related errors (Ganskopp and Johnson, 2007), some alternatives to GPS for tracking the animals in pastures have been evaluated. The application of outdoor image analysis using top-view cameras, which are currently used indoors to monitor animals, was evaluated. In fenced pastures, Bonneau et al. (2020) applied a framework that combined low-cost time-lapse cameras, machine learning, and image registration to monitor the location of animals belonging to two flocks of goats. The obtained precision and sensitivity were 90% and 84.5%, respectively. However, these authors also observed that some factors including topography, animal size (with newborns being hardly detected), and objects on the background could reduce the sensitivity to 70.7% and the precision to 83.8%. However, the main advantage of the framework was its financial cost, which was significantly lower than that of GPS. Camera lapse has been applied to accurately determine the number and position of cattle at waterpoints in order to calculate enteric methane emissions using micrometeorological methods (Benvenutti et al., 2015). Image analysis provided more reliable and accurate estimates of the position and number of animals located within 55 m of the camera, compared with GPS collars. Lastly, UAVs have also been proposed for monitoring and tracking animals in extensive pastures (Jung et al., 2016; Wamuyu, 2017; Vayssade et al., 2019; Li and Xing, 2019)

Pasture evaluation and grazing management

Assessing pasture availability and quality from remote sensing

The quality and quantity of pasture play a crucial role in the management of pasture-based systems. These methods are traditionally evaluated through labour- and time-consuming methods (i.e., field measurements and chemical analysis). Owing to their flexibility in acquiring data over a large range of time and space, remote sensing (**RS**) techniques represent a rapid and effective method for pasture monitoring. In grassland monitoring, RS data are normally acquired through three different types of sources: optical sensors, synthetic aperture radar sensors, and light detection and ranging sensors (Wachendorf et al., 2018). The most commonly used optical sensors are based on space-borne sensors. These acquire multispectral images, at different spatial and temporal resolutions, to develop a grass production or a quality estimation regression model driven by field samples and vegetation indices, for example, normalised difference vegetation index or biophysical variables (e.g., leaf area index). For example, Jin et al. (2014) estimated grassland biomass and its spatiotemporal dynamic variation among different years in three different regions of China using MODIS satellite images. MODIS satellite data have also been coupled with simulation models for the prediction of grassland productivity as well (Maselli et al., 2013). Furthermore, leaf area index derived from SPOT images has been shown to have good accuracy (R^2 = 0.68) in biomass estimation (Dusseux et al., 2015).

Mountain pastures are also an important feed resource for livestock. In this scenario, satellite RS can cover large areas, such as mountain meadows. However, as explained by Barrachina et al. (2015), high heterogeneity in grass composition and the effects of meteorological variables make biomass prediction less accurate. Despite this, vegetation index values obtained from Landsat-5 satellite images were successfully applied in mountain areas to model above-ground biomass.

The evolution of satellite programs allows free data acquisition in a shorter time and with higher resolutions. For example, the Sentinel-2 multispectral imager can provide data with a spatial resolution of 60–10 m in a spectral range of 440–2200 nm, every five days. Sentinel-2 images were used, for instance, to predict above-ground biomass across different fertiliser treatments (R^2 = 0.81) in red edge bands (Sibanda et al., 2015). Likewise, good results were obtained with Sentinel-2 images in the estimation of pasture quality and its spatiotemporal variability (Lugassi et al., 2019). Although satellite images allow measurements over large areas, the images are not always available owing to changing weather conditions (e.g., cloudy days). To overcome these issues, satellite-based synthetic aperture radar RS, integrated with optical remote sensing (Landsat-8 and Sentinel-2) might also be used in pasture monitoring, as they provide high spatial resolution in adverse weather conditions (Wang et al., 2019).

Recent studies have involved the combination of satellite data and optical sensors (e.g., multispectral cameras) mounted on UAVs (Liu et al., 2019). Although UAVs are also negatively influenced by weather conditions, their flight missions are more flexible, and the sensors can reach finer spatial resolutions than non-commercial satellite images. For instance, drone-based multispectral camera sensors can reach a spatial resolution of <5 cm with a flying altitude of 45–50 m in the spectral range of 550–790 nm (Fawcett et al., 2020). Despite this, only a few studies in the scientific literature have looked at applications of UAV-based systems for assessing grasslands. Promising results have been reported by Askari et al. (2019), who showed that the ratio of red and green bands had the maximum impact on the prediction of CP using a low-cost multispectral camera. Other relevant studies were conducted by Gao et al. (2019), who used UAV multispectral images to predict DM and CP, and by Insua et al. (2019), who developed a UAV-modelling approach to evaluate the nutritive values of grass-based pasture.

Future commercial development of RS techniques in grassland monitoring remains a challenging endeavour for research because a large amount of data sampling in the field is still required for regression analysis. However, empirical evidence on pasture production shows that RS techniques can decisively support farmers towards sustainable herd management, for instance, helping them choose the right stocking rate in relation to the availability of forage, optimising pasture efficiency, and reducing labour requirements. Moreover, when coupled with other precision livestock tools (e.g., virtual fencing), a predictive system could be useful for encouraging rotational grazing management systems.

Animal behaviour, activity time budgets, and grazing intake

The first technology applied in grazing research was GPS, which has been used to study the grazing behaviour and preferences of herds or individuals (Table 3). For instance, spatial and vegetation preferences of cattle and sheep have been investigated (Putfarken et al., 2008; Ganskopp and Bohnert, 2009; Schoenbaum et al., 2017), as well as the effect of social hierarchy on the exploitation of pasture resources by sheep flocks (di Virgilio and Morales, 2016). GPS was used to assess cow-calf contact patterns, activity, and pasture use patterns of heritage and desert-adapted commercial beef cows and young calves (Nyamuryekung'e et al., 2021). GPS was recently used to track the interactions between Iberian pigs and wild ungulates during the 'montanera' period (Triguero-Ocaña et al., 2020).

An exception to the predominant use of GPS in monitoring animal behaviour and pasture use was found in poultry. In this sector, the only studies identified on the application of PLF technologies in pasture-based systems reported the use of RFID on laying hens to monitor the impact of different stocking densities on outdoor resource utilisation (Campbell et al., 2017a) and the individual ranging behaviour according to flock size (Gebhardt-Henrich et al., 2014). This is likely due to the limited range of outdoor hens compared to the distance travelled by other pastured species.

More recently, GPS-collared cattle were used to model spatial patterns of phosphorus depletion and accumulation in mountain pastures during summer grazing (Koch et al., 2018). Similarly, urination frequency, nitrogen load in each urination event and spatial distribution patterns of urine were investigated for grazing sheep and cattle using a GPS unit coupled with a thermistor suspended below the vulva which recorded urination events as changes in temperature (Betteridge et al., 2010).

Beyond the spatial distribution of animals and preferred grazing sites, GPS data are able to provide useful information for decoding and classifying a series of animal activities (Anderson et al., 2012) including changes in walking, lying, feeding, and ruminating patterns, all of which are important signs of alterations in animal welfare. As animal welfare has become a priority in recent years, technologies aimed at its assessment have been developed at a

Table 3
Studies on grazing behaviour and activity budget for different livestock species reared in pasture-based systems.

Species	Technology	Location	System	*n*	Country	Aim	
Sheep	Tri-axial accelerometer	Under the jaw		5	Australia	Detecting jaw movements	Alvarenga et al. (2020)
Sheep	Tri-axial accelerometer	Under the jaw	Semi-improved pasture (0.3 ha)	4	Australia	Behaviour	Alvarenga et al. (2016)
Beef cattle	GPS	Collar + head-halter	Semi-desert rangeland	17	United States	Behaviour	Anderson et al. (2012)
Dairy cattle	Inertial Measurement Unit	Collar, head	Pasture (0.19 + 1.4 ha)	19	Belgium	Classify grass intake and rumination unitary behaviours	Andriamandroso et al. (2017)
Sheep and Cattle	GPS + Thermistor	Sheep's back, vulva	Pasture (2.9 ha + 11 ha)	20 sheep + 12 cows	New Zealand	Develop urine sensors and GPS units to quantify daily urination event spatial distribution of urine patches	Betteridge et al. (2010)
Dairy cattle	Wide-frequency inward microphone	Head	Natural pasture	25	United States	Forage intake and grazing behaviour	Chelotti et al. (2016)
Sheep	GPS	Collar	Pasture (80–1 000 ha)	19	Argentina	Effects of animals' social context on grazing behaviour	di Virgilio and Morales (2016)
Beef cattle	GPS	Collar	Pasture (3 × 800 ha)	12	United States	Grazing behaviour	Ganskopp and Bohnert (2009)
Cattle	GPS, tri-axial accelerometer	Collar	Pasture (20 ha)	13	China	Classifying livestock behaviour and defining the GPS optimal time interval	Gou et al. (2019)
Beef cattle	Tri-axial accelerometer	Collar	Individual pasture plots (<0.22 ha)	10	Australia	Pasture intake by grazing behaviour	Greenwood et al. (2017)
Dairy cattle	GPS	Collar	Alpine pasture	3	Switzerland	Quantify P fluxes, areas of P depletion and accumulation, determine the P budget	Koch et al. (2018)
Dairy cattle	Microphone, pressure sensor (noseband), visual observation	Head	Sown plots	9	Argentina	Comparing (visual observation, pressure sensor and acoustic recording to quantify the number of bites	Nadin et al. (2012)
Cattle, sheep and goat	Microphone	Forehead and collar (Cattle); Horn (sheep and goat)	Pasture	3 + 6 + 6	United States, Israel, United Kingdom	Validating an algorithm for jaw movement identification	Navon et al. (2013)
Dairy cattle	Two and three-axis accelerometers	Collar	Daily pasture	20 + 10	Denmark	Grazing time and feed intake	Oudshoorn et al. (2013)
Dairy cattle	Three-axis accelerometers	Collar	Daily pasture	24	United States	Validating an ear tag accelerometer sensor	Pereira et al. (2018)
Cattle and sheep	GPS	Collar	Semi-natural pasture (180 ha)	3 + 3	Germany	Grazing behaviour and preference according to animal's species	Putfarken et al. (2008)
Sheep	Pressure sensor	Noseband	Pasture (0.25 ha)	8	United Kingdom	Grazing behaviour	Rutter et al. (1997)
Dairy cattle	Noseband pressure sensor, 3-axial accelerometer	Head, leg	Daily pasture	12	Ireland	Forage intake and grazing behaviour	Werner et al. (2018)
Dairy cattle	Tri-axial accelerometer	Collar	Daily pasture	6 + 12	Ireland	Grazing behaviour	Werner et al. (2019)
Beef cattle	Tri-axial accelerometer	Collar	Rotational grazing paddocks (1–10 ha)	8	Australia	Drinking behaviour and water intake	Williams et al. (2020)
Beef cattle	Single-axial accelerometer	Collar	Mixed sown paddock (0.85 ha)	6	Japan	Differentiating between foraging and other activities	Yoshitoshi et al. (2013)

Abbreviations: GPS = Global Positioning System.

rapid pace. This is the case for accelerometers, which have become the primary tools used for recording activities. Examples of accelerometers used to enhance animal welfare have been reported to detect lameness in grazing dairy (O'Leary et al., 2020) and beef (Poulopoulou et al., 2019) cattle. They have also been used to record and classify standing, lying, resting, ruminating, and grazing behaviours in cattle and sheep (Yoshitoshi et al., 2013; Alvarenga et al., 2016; Werner et al., 2019). In addition to their low energy requirement compared to GPS devices, accelerometers are very accurate in detecting head position, which allows discrimination between grazing, lying and standing (Pereira et al., 2018). Several devices embedded with accelerometers are already available in the market for dairy and beef cattle (e.g., Moomonitor®, Dairymaster; Allflex SenseHub®, SCR Engineers Ltd.; Ceres tag®, CeresTag Pty Ltd; IceTag® and IceQube®, IceRobotics, Ltd, see Table 2). These devices offer farmers real-time monitoring of animal welfare, building up historical activity trends at the animal and herd levels, thus alerting the farmer to abnormal behaviour. An interesting application of accelerometers, already offered by several market monitoring devices, is the detection of hyperventilation and, thus, heat stress (e.g., Allflex SenseHub®, SCR Engineers Ltd., see Table 2).

GPS and accelerometers have been used in combination. Gou et al. (2019) compared three methods to classify livestock activity in pastures and observed that the tri-axis accelerometer model was the most precise (96% accuracy), but location could be very important in rangeland systems; thus, the GPS-tri-axis model or GPS alone (90% accuracy) was more suitable for grazing animals. Moreover, accelerometer technology has low energy requirements, and their joint application can enhance the GPS battery lifespan by setting the GPS to actively record only when the accelerometer detects a movement at a certain speed (Terrasson et al., 2016).

Recently, the use of Inertial Measurement Unit (**IMU**) sensors has been reported. The IMU is a combined device which includes several different sensors (accelerometer, gyroscopes, magnetometer) that are able to measure linear acceleration, rotation angle (pitch, roll, and yaw) and angular velocity. An IMU from a common mobile phone was used on cattle (Andriamandroso et al., 2017), obtaining 92% of accuracy in activity classification, reaching 95% for rumination activity.

Focusing on grazing activity, research went deeper to detect jaw movements in order to classify them as bite (grabbing and tearing off), chew (crashing), and bite-chew (overlap of chewing and biting activities) movements, and to count their number and duration, with the objective of discriminating between grazing and ruminating. The assessment of jaw movements has also allowed for a novel approach to estimate feed intake in pastures. For this purpose, two types of sensors have been used: pressure sensors and acoustic sensors (Rutter et al., 1997; Clapham et al., 2011). As reported by Rutter et al. (1997), pressure sensors consist of a noseband made of a silicon tube packed with carbon granules. The electrical resistance of the sensor changes as the animal opens or closes the jaw. These changes were recorded and subsequently analysed using software to determine the activity cycles.

In contrast, acoustic sensors mainly rely on a microphone located on the head of the animal or near the mouth, as described by Clapham et al. (2011). The acoustic signal was recorded, and frequency, intensity, duration, and time between events were used to classify them as bite and chew events. However, the signal classification was performed later. To lengthen monitoring and to reduce the storage needed, systems with an embedded processor were developed to perform algorithms for real-time and automatic classification of acoustic signals in chewing, bite, and chew-bite events in different livestock species (cattle, sheep, and goats) (Navon et al., 2013; Chelotti et al., 2016).

Algorithm implementation for real-time classification of acoustic signals has greatly increased the feasibility of using this method to assess jaw movements. Indeed, when compared to pressure sensors, the acoustic technique more precisely identified bite, chew, and chew-bite events, whereas pressure sensors tended to misclassify a significant proportion of chews as bite (Nadin et al., 2012).

Direct estimation of grass intake by accelerometers was performed according to different methods including by collar-mounted devices recording daily activity budgets, such as grazing (Greenwood et al., 2017) or with the aid of bite counts (Oudshoorn et al., 2013). A commercial on-farm system was also implemented by combining a noseband pressure sensor for jaw movement detection and a tri-axis accelerometer for activity monitoring, showing a high level of accuracy in measuring feeding behaviour (Werner et al., 2018). Alternatively, the accelerometer was mounted under the jaw with the specific purpose of assessing jaw movements and then grass intake according to bite events (Alvarenga et al., 2020). However, data collected through sensors should be carefully used to estimate grass intake to ensure the fulfilment of nutritional requirements. Pasture can vary in composition and quality, and bite speed and bite mass differ owing to sward height, density, and DM concentration (Wilkinson et al., 2020).

Few applications of accelerometers and RFID have been reported to study the drinking behaviour and herd water intake of grazing animals (Williams et al., 2020). The approach relies on the unique head-neck position of cattle during drinking, which can be well identified by a neck-mounted tri-axial accelerometer. Water intake was calculated using a water trough equipped with a water flow metre. The combination of these technologies allowed the number, duration, and frequency of visits per animal to a water point, the number and duration of drinking events per animal visit, and the time each animal spends drinking to be recorded (Williams et al., 2020). Thus, further developments could allow the farmer to monitor that herd water intake needs are met, even in environmentally challenging situations such as during droughts and the dry season.

Most of the listed technologies on grazing activity and feed intake quantification may not have a substantial commercial application under farming conditions, but they are helpful tools for understanding the spatial utilisation of pastures, vegetation preferences, and excretion patterns of grazing livestock. Therefore, the information collected can be translated into best practices and tools for active management of the herd with the final aim of maintaining pasture quality and biodiversity, as well as controlling overgrazing and grassland degradation (Bailey et al., 2018). For instance, a combination of GPS, accelerometer, and UAV was used to understand the impact of feed restriction in gestating sows at pasture on their foraging behaviour and on vegetation cover (Aubé et al., 2021).

UAVs were also used to assess grazing preferences of several livestock species. This is an interesting upcoming tool to support farmer's decisions on creating specific grazing groups according to animals' age or behaviour, or on setting the correct stocking rate according to available resources (Trukhachev et al., 2019).

Virtual fencing

Virtual fencing (**VF**) is a recently implemented system aimed at controlling grazing. Through VF, farmers can choose and delineate an area where livestock can graze. The traditional physical boundary is replaced by an acoustic stimulus; when the animal is approaching the VF, an acoustic cue warns it to stop. If the animal ignores the cue, it receives an electric shock as a positive reinforcement. The system comprises collars with a GPS tracker and a battery-powered device that administers the electric shock.

Currently, most VF systems rely on GPS locators, allowing greater flexibility in choosing grazing areas (Rutter, 2017). The rising interest in VF solutions has highlighted two main issues: animal welfare (Campbell et al., 2017b) and battery performance. The first issue can be addressed by developing proper training protocols based on associative learning methods (Kearton et al., 2019) and by investigating changes in activity time budgets (walking, lying, standing) and stress-related parameters. No (Campbell et al., 2017b) or few differences (Campbell et al., 2019b) in time spent lying (less than 20 minutes for every training session) were observed between cattle managed with VF compared to electric tape boundaries, whereas no differences between treatments were observed in faecal cortisol metabolite concentrations. An interesting output of several studies on training and application of VF was the large variability between animals in the time required for learning to respond to the audio cue (Campbell et al., 2019b; Lomax et al., 2019; Marini et al., 2019). Verdon et al. (2020) observed that less fearful heifers were more unresponsive to audio and electrical stimuli.

From the perspective of wider commercial diffusion, the system should ensure that all the animals can learn how to properly interact with the system, and individual variability should be limited to the time needed to learn. Moreover, herd behaviour should be studied, as the learning process might be socially facilitated (Marini et al., 2018; Campbell et al., 2019a). This does not exclude the possibility that the size of the group can affect the success of training. Indeed, in large flocks, sheep are known to form subgroups, and the responses of individual sheep to passive recruitment can be affected by group size (Marini et al., 2019). The application of VF for pasture management should always consider pasture availability to ensure animal welfare. Increased hunger states may challenge the effectiveness of VF technology as feeding is the major attractant for animals (Verdon et al., 2020). VF can also be applied in a more dynamic situation than delineating an exclusion zone containing an attractant. Campbell et al. (2017) tested GPS-based VF, gradually shifting the limits over 22 days and enabling the animals to enter greater percentages of the grazing paddock. Animals learned the VF location within approximately 48 h, but as the inclusion zones changed, animals were responsive to the audio cue and did not fear the old boundaries. Similar results were also observed by Lomax et al. (2019) in dairy cattle. VF has also proved to be an interesting tool for temporarily excluding livestock from environmentally sensitive areas, such as cattle from a riparian zone (Campbell et al., 2019a). Moreover, virtual fencing systems on the market (i.e., eShepherd®, Agersens, AU; Halter®, NZ; Vence®, CA, USA; Nofence®, NO; see Table 2) offer farmers additional tools to improve livestock management at pasture, such as tools to optimise rotational or strip grazing, and real-time animal monitoring to detect changes in behaviour denoting heat, lameness, or calving.

Due to animal welfare concerns, some attempts to manage the herd without electric stimulus as negative reinforcement have been conducted using only the audio cue as a deterrent (Umstatter et al., 2013). However, the results did not ensure the same level of effectiveness in excluding animals from the chosen areas. As an alternative, audio delivery devices embedded in collars or harnesses have been proposed to recall animals towards a feed attractant, which might assist the farmer in grouping the animals for management operations (Umstatter et al., 2015).

Herd management

Systems consisting of GPS trackers and aerial pasture monitoring have been tested as supporting tools for grazing planning to avoid overgrazing and grassland degradation. Li et al. (2020) proposed a cloud grazing management and decision system based on WebGIS that was able to display the herd's real-time position, its historical trajectory, and to monitor and estimate grassland growth and intake by both UAV and satellite RS images. This information was available in real-time for end-users, providing a decision-making basis for herd management. Similarly, di Virgilio et al. (2018)—combining the data retrieved by an animal-attached multi-sensor tag, consisting of a tri-axial accelerometer, tri-axial magnetometer, temperature sensor, and GPS with landscape layers from GIS—developed a PLF methodology for the management of Merino sheep in Patagonian rangelands. The authors used the acquired data on behavioural patterns, feeding rates, predation risk, competition for grazing resources, landscape, and environmental parameters to estimate the energy balance and to predict individual growth, survival, and reproduction.

As demonstrated by VF devices on the market, this technology has already become a system acting as a "virtual shepherd," thanks to the integration with other sensors on the animal, i.e., accelerometers for activity budgets, and external data such as weather forecasts and topographic data, to identify risky areas or areas suitable for feeding and pasture availability by RS (Terrasson et al., 2017). Moreover, Jung and Ariyur (2017) theorised that multiple UAVs could be used to gather herds. Similar experiences were reported in Australia and New Zealand by Yinka-Banjo and Ajayi (2019), where UAVs have successfully been used to muster sheep and cattle and to guide the animals to feeding, drinking, or milking areas. However, very little research has been carried out on domestic animals, although the use of UAVs for wildlife monitoring is steadily increasing (Barbedo and Koenigkan, 2018).

Several systems on the market consisting of combined sensors already provide farmers with complete information on health, reproductive status, heat stress, localisation, and calving, and a non-exhaustive list of these solutions is given in Table 2.

Reproduction monitoring: oestrus, parturition, pedigree

Oestrus

Owing to the economic importance of reproductive traits and the widespread use of artificial insemination, the first sector to apply new computerised methods was dairy farms. Among the early automatic methods for oestrus detection, pedometers appear to be the most widespread (Abeni et al., 2019). In recent years, accelerometers and integrated monitoring systems with embedded accelerometers have become popular for monitoring animal activity and predicting oestrus (Brassel et al., 2018; Adenuga et al., 2020).

Nevertheless, the need for remote oestrus detection in cattle and sheep strongly depends on breeding management; if it includes planned mating, real-time monitoring of oestrus is of pivotal importance for herd management. Andersson et al. (2016) successfully tested a wireless intravaginal probe for grazing cattle. It worked using a combination of conductivity, temperature, movement, and position to detect oestrus. The probe's battery duration was estimated to be approximately five years using a measurement interval of 30 min and a transmission range of 100 m. To address the additional power requirements of transmission over long distances, such as for dispersed herd grazing in a natural environment, the authors foresaw the implementation of the system, including battery-powered repeater nodes in a collar.

Parturition

The simplest tool used for parturition events in pasture-based systems was a GPS-embedded collar. In gestating sheep, GPS technology was able to identify parturition time by changes in daily and hourly walking means and speed and by changes in the spatial movements of ewes in the days immediately after the presumed parturition (Fogarty et al., 2020). Reliable prediction of calving time is also very important for cattle kept in pastures. Indeed, during calving, farmers' quick intervention could help to avoid calving loss in cows in poor health or with primary labour insufficiencies, as well as reduce potential calf injury caused by the mother or by environmental factors (Calcante et al., 2014). However, to ensure prompt intervention, the exact location of the animal needs to be provided. For this purpose, Calcante et al. (2014) patented a GPS-calving alarm device that alerts the farmer via SMS. The SMS includes birth event date and hour, animal ID, and geographical coordinates of the partum point. The GPS coordinates are imported into a common mobile application. Considering the component's lifespan, the device was able to cover up to 10 calves/year at a unitary cost of € 31.5 per birth.

In addition to oestrus detection, accelerometers have also been used for calving detection. The sensor is mounted on the tail and detects tail movements associated with approaching calving. Alerts are sent to farmers by app notification or GSM (CalveSense®, SCR Engineers Ltd.; Moocall®; smaXtec®, GmbH, see Table 2). The systems also work in pasture-based systems owing to embedded SIM or solar-powered antennas that transmit the signal locally received by animal-mounted devices.

Pedigree

Grazing herds or flocks often consist of fertile females and males; in this situation, the main problem is to reconstruct the offspring's pedigree rather than monitoring oestrus. Some systems to rebuild maternal pedigree are mainly based on RFID technology. To determine maternal pedigree in Australian sheep flocks, a system called Pedigree Matchmaker® was built using software designed by the Cooperative Research Centre for Sheep Industry Innovation (Sheep CRC). It permits the attribution of each lamb to its ewe by recording the order in which RFID tags are read as animals pass near the tag reader entering in a fenced space containing an attractant. The pairs of animals that moved together corresponded to the lamb-ewe pairs. Although 21 days of recording was needed to achieve 80–85% of maternal parentage in three flocks of 100–200 ewes (Richards and Atkins, 2007) and one herd of 41 beef cows (Menzies et al., 2018b), this system was considered labour-saving and less expensive than manual catching or DNA matching. It can also improve the genetic progress in pasture-based livestock systems. Similarly, still working on the proximity between ewe and lamb, Sohi et al. (2017) proposed a matching system based on Bluetooth, which showed a higher accuracy in a shorter time than Pedigree Matchmaker. However, although this system did not require any walk-by structure to register the pedigree, it involved animal handling to put on and remove Bluetooth tags before obtaining the maternal pedigree. In the grazing context, it may be challenging to apply and recover animals into walk-by structures.

Some solutions based on RFID-built pedigree are already available in the market (e.g., DataMuster®). In this case, the problems related to data collection, storage, and transmission were solved, offering opportunities for farmers to have the system working online by GSM or wireless connection or offline by storing the data.

In some cases, tracing paternal parentage can also be important. An initial attempt was made by Abell et al. (2017), using accelerometer data and various classification algorithms (random forest, random tree, and decision tree), to tentatively predict bull behaviour events in a multiple-sire pasture. The authors succeeded in discriminating between lying, standing, walking, and mounting; however, mounting event accuracy only ranged from 74 to 80%, and was considered inadequate. Another system to assess contemporary parentage and oestrus in sheep was proposed by Alhamada et al. (2017). The system was composed of an RFID device fixed with a harness on the male, whereas the female had an electronic identifier that recorded the accepted mounts.

Predation

Predation of grazing livestock is a major issue in many countries. The difficulties of continuously monitoring the animals, the unpredictable movements of wild predators, and the difficulty of quickly reaching the livestock being attacked have been major issues for the successful reduction, or at least containment, of this phenomenon. With the advent of new technologies, different approaches have been attempted in different countries. In the USA, where predation events against grazing cattle are mainly caused by wolves, Clark et al. (2020) tried to combine GPS data on wolves' preferred rendezvous sites and spatial cattle resource selection patterns during the summer grazing season. Their objective was to predict the spatial risk of wolf-cattle encounters and associated predation events using spatial models. A wolf-cattle encounter risk map was developed to identify where, on different landscapes, predation was most likely to occur. The research was validated only in a few small areas but provided a predictive model with interesting applications for farmers, if further implemented and maintained by regularly collecting data on tracked wolves and predation events.

In contrast, Manning et al. (2014) used GPS devices to quantify the behavioural responses of two sheep flocks under attack. The authors observed that centripetal rotation (circling behaviour of the flock, with individual sheep seeking the centre) of animals occurred in 80% of the simulated predation events, and the velocity of sheep was significantly higher during simulated events. The spatial–temporal data derived from GPS devices, with appropriate mathematical modelling, might be used to identify predation and alert the farmer. Finally, Sendra et al. (2013) proposed a prototype of a smart wireless sensor network composed that measures the frequency of heart and corporal temperature. Data were interpreted by a smart algorithm able to detect episodes of collective stress on the flocks of goats and sheep caused by any predator attack overnight. When an attack was ongoing, the system automatically activated audible and visual alarms to scare off predators and sent an alarm signal to the farmer. The prototype should be tested under farm conditions, but it presents some useful features for further implementation. For instance, it is self-sufficient considering the energy limitations of field conditions. It is recharged by a solar panel, and a control unit limits its operation to nighttime. Moreover, providing an immediate response to scare predators while waiting for human intervention could have an actual impact on avoiding killings.

Future perspectives and conclusions

Applying PLF in pasture-based systems provides several advantages, as we have discussed in detail. Livestock research has already benefitted from PLF technologies providing access to a large amount of information on animals' grazing behaviour and activities without human disturbance and for long periods of time, as well as in remote locations that are difficult for human observers to access. The opportunity to monitor the animal, regardless of its location and the moment of the day (i.e., also during night), is an undeniable benefit for the farmer, who can be immediately warned in case of abnormal behaviours and, therefore, promptly intervene (Waterhouse, 2019). Moreover, wearable sensors and field technologies can collect information useful for overall herd management, from pedigree reconstruction to the planning of medical treatments or feeding supplementation according to pasture availability. In the context of climate change, the development of tools to monitor several climatic parameters in a pasture could become of inestimable importance to support farmers in decision-making and to prompt interventions for livestock before the onset of welfare issues. Remote sensing of pasture availability, identification (and exclusion) of environmentally sensitive areas, and virtual management systems could become a pivotal tool for grazing management and grassland preservation (Rutter, 2017). Moreover, further development of PLF for animal production could also involve the final production phases, such as transportation and transformation, covering the entire supply chain and improving traceability of products.

Nevertheless, the development and application of PLF technologies in livestock farming are expanding both in indoor/confined and pasture-based livestock systems. Research in rangelands has greatly benefitted from such solutions; however, PLF use among farmers in rangeland systems is still limited compared to intensive livestock systems. This is likely related to several hurdle characteristic of pasture-based systems that are still unsolved.

Firstly, battery lifespan must guarantee long-term functionality and minimum maintenance to avoid frequent capture operations. To overcome this issue, several strategies have been tested, including more battery performance (as long as battery size and weight remain wearable by animals), more efficient duty cycles, compression of data, and new energy harvesting techniques (Llaria et al., 2015; Zhang et al., 2018). Finally, solar panels are increasingly used to extend the battery lifespan, even if their performance depends on the climatic conditions. The second issue is related to data management under open-field conditions. The transmission coverage range can be challenging, especially in mountain areas or tree-covered pastures (Llaria et al., 2015). This means that devices for PLF application in rangelands need to ensure adequate storage capacity to maintain the collected data until the conditions are suitable for transmission, or efficient wireless delivery systems. The improvement of these latter technologies might be especially useful from the perspective of real-time monitoring. Finally, a certain flexibility is required because free-ranging animals have plenty of feeding and water sources, and can move for very large distances, so identifying a reliable system for downloading and transmitting the data often is site-specific and very flexible solutions are needed (Kwong et al., 2011).

Regardless of technological constraints, the on-farm application of PLF technologies must meet some economic and operational requirements, such as (i) fitting within current management practices, (ii) requiring no additional labour, (iii) being economical and more advantageous than current management, (iv) providing at least the same accuracy as traditional methods, and (v) having a user-friendly design (Halachmi et al., 2019). From an economic perspective, an important factor that should be considered is that farms rearing animals at pasture often have lower returns than intensive farms, so investing in PLF technologies is not always affordable. The feasibility of applying PLF in pasture-based systems is mainly related to significant labour reduction, both to finance the purchase of the PLF technologies and to obtain tangible benefits from the investment (Waterhouse, 2019). Some concerns also targeted the loss of jobs, the deskilling of the remaining positions, and the possible increase of labour due to false-positive alerts and reports that need to be checked in rushed environments (Werkheiser, 2020).

Ethics approval

The authors did not use any live animal to conduct this review.

Data and model availability statement

None of the data were deposited in an official repository

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Declaration of interest

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