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REVIEW ARTICLE

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How do we feed grazing livestock in the future? A case for knowledge-driven grazing systems

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Abstract

Grassland degradation has been observed worldwide and is often a result of overexploitation or abandonment. Knowledge-driven and precise grazing management is required to use grasslands' potential in a sustainable way. Information gaps lead to inefficiencies in grazing land management and ecosystem service provision. Rapid advances in automated sensors and information technologies for information acquisition on herbage availability, controlling animal grazing behaviour and setting up data-driven decision support tools have the potential to improve grazing management. Sensors and IT-based methods allow spatiotemporal dynamics in herbage mass and quality and sward structure and botanical composition to be obtained automatically. These monitoring methods enable a spatially and temporally precise adjustment of the forage allowance and stocking density. Virtual fencing (VF) is an innovative digital tool for fine-tuned spatiotemporal control of grazing animals. VF enables farmers to adjust grazing flexibly and dynamically by moving the virtual borders on a mobile user interface and sending new coordinates to the GPS receiver unit on each animal's VF collar. VF promises high efficiency with no obvious negative impacts on animal welfare. The potential of VF is enormous, but its economic viability still needs to be verified and its acceptance by authorities and the public needs to be supported. A decision support system that optimizes grazing management and agronomic and ecological outcomes by integrating and analysing multiple data at high spatial and temporal resolution can provide sufficient knowledge and confidence in grazing management decisions. Integration of key technologies into a holistic concept can take grazing management to the next level.

KEYWORDS
ecosystem services, grazing management, livestock grazing, mitigating trade-offs, precision farming, technological innovations

1 | INTRODUCTION

The projected increase of the human population to around nine billion by 2050 (FAO, 2018) requires increased sustainability of agriculture systems (Kleijn et al., 2019). Over the last decades, the balance of meat production has shifted from ruminant (cattle, sheep) largely

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forage-based systems to monogastric (poultry, pig) livestock systems, which is of concern as these mainly depend on feed grown on arable land (Martens et al., 2012). Furthermore, total meat production globally is projected to increase further by the end of the present decade (OECD/FAO, 2020). In many high-income countries there has also been a shift towards more intensive cattle production systems for meat and dairy production with an associated reduction in the use of sustainable, grassland-based livestock systems (FAO, 2017). For instance, in Central Europe, dairy cows often do not graze and are predominantly housed indoors (Läpple & Sirr, 2019). Moreover, they are mainly fed with silage, and concentrated feed (Schingoethe, 2017) as dairy farmers are under pressure to maximize the total annual milk output per cow whilst also occupying a minimum area of land (Knaus, 2016).

Grasslands are one of the most important biomes on earth (White et al., 2000); they contain 30% of the world's carbon stocks (Scurlock & Hall, 1998) and their carbon sequestration role is estimated to offset around 590 billion tonnes of carbon dioxide emissions (Burney et al., 2010). Thus, their sustainable use and management are essential for their capacity to support ecosystem services, including biodiversity, as well as having socio-economic implications for rural communities (Michalk et al., 2019). Grasslands provide the basis for economically crucial roughage-based livestock farming and supply people worldwide with high-quality food in terms of milk and meat. Their multiple ecosystem services are linked to grassland diversity (Bengtsson et al., 2019; Werling et al., 2014). Degradation of formerly diverse grasslands has been observed worldwide, so that they no longer supply multiple ecosystem services (Manning et al., 2018; Michalk et al., 2019) and this trend is predicted to increase. Degradation of grasslands results in reduced productivity, reduced soil C sequestration and higher net greenhouse gas emissions, higher nitrogen leaching and runoff, land sparing, water pollution, and biodiversity losses (Bardgett et al., 2021; Gang et al., 2014; Kayser et al., 2018). Thus, the perspective and aim of future grassland management across all regions of the world must be to balance production and environmental goals. In areas with temperate climates, grazed herbage provides a highly efficient, nutritious and cheap energy supply for ruminants (Dillon et al., 2005). Thus, grassland-based ruminant production offers a sustainable alternative to intensive, non-grazing systems (e.g., Lawrence et al., 2019). Notably, for sustainable grazing management, timely, precise allocation of the grazing area according to the daily nutritional demands of the animals and herbage availability is essential (e.g., Curran et al., 2010). Precise and sustainable grazing management can optimize grassland utilization and fulfil a cow's nutritional requirements in terms of enabling milk yields of at least intermediate output (Klootwijk et al., 2019). Research has recently highlighted that grazing animals are essential for enhancing structural and biological diversity and ecosystem services in grasslands (Johansen et al., 2019; Kapás et al., 2020; Navarro & Pereira, 2015). Moreover, there are important animal welfare benefits associated with outdoor grazing (Burow et al., 2013). Grazing livestock systems also have potential to reduce the use of imported feed and of the greenhouse gas emissions associated with its cropping and transportation (Weiss & Leip, 2012). To counteract the dependence on arable crops and to exploit the potential of grasslands, it is necessary to ensure that cattle are brought back onto grazing land in a knowledge-based and sustainable manner.

For sustainable grazing and balancing the trade-offs in livestock productivity and other ecosystem services, there are promising opportunities for precision farming technologies to manage grazing animals and deliver timely and precise information about the complex animal–plant system on the grazing land. Although precision farming technologies have been used in arable farming for many years, they have been much less used in grazing livestock (Bahlo et al., 2019; French et al., 2015; Schellberg et al., 2008). However, following current advances in the development of novel smart farming technologies, there is more potential for applications in livestock farming.

In this review, we focus on the current challenges in achieving sustainability of grassland-based livestock production and we provide ideas for sustainable livestock grazing by knowledge-driven concepts in terms of precision farming (PF) and decision support tools. Our analysis is presented in terms of the following: (i) the global switch towards livestock systems that depend on feed grown on arable land rather than grassland-based systems; (ii) an assessment of the current state of global grazing systems; and (ii) the information gaps and challenges for sustainable grazing management; and (iv) an overview of the future perspectives including opportunities for smart farming technologies and tools that can enable farmers to improve their grazing management and to use the potential of grassland more efficiently.

2 | INCREASE IN LIVESTOCK SYSTEMS THAT DEPEND ON FEED GROWN ON ARABLE LAND

The switch towards more crop-dependent livestock systems has been driven by substantial changes in socioeconomics arising from the growth of human population, industrialization, and globalization, and scientific progress, especially since the Green Revolution of the 1950s and 1960s. This intensified production modes and reinforced dependency on crops from arable land as animal feed (Godde et al., 2018). There has been shift towards greater use of monogastric livestock systems (pig, poultry) for meat production in the past three decades, with pork having the highest global production level at approx. 173 Mt meat, followed by poultry (128 Mt) and beef (73 Mt) in 2019 (FAO, 2021). Pork production requires about 128 m^2 of arable land to supply the animal feed per one-kilogram of protein for the human diet, compared with 36 m^2 of arable land for the equivalent amount of chicken protein production and 30 m^2 for beef protein production. Globally, forage intake of beef cattle and dairy cows mainly consists of roughage grown on grazing land. Nevertheless, beef meat and cow milk production also depend considerably on feed grown on arable land (Figure 1; data derived from Flachowsky et al., 2017). Pigs and poultry are predominantly housed indoors and fed concentrate diets consisting of approx. Sixty percent grain as maize, wheat, barley or

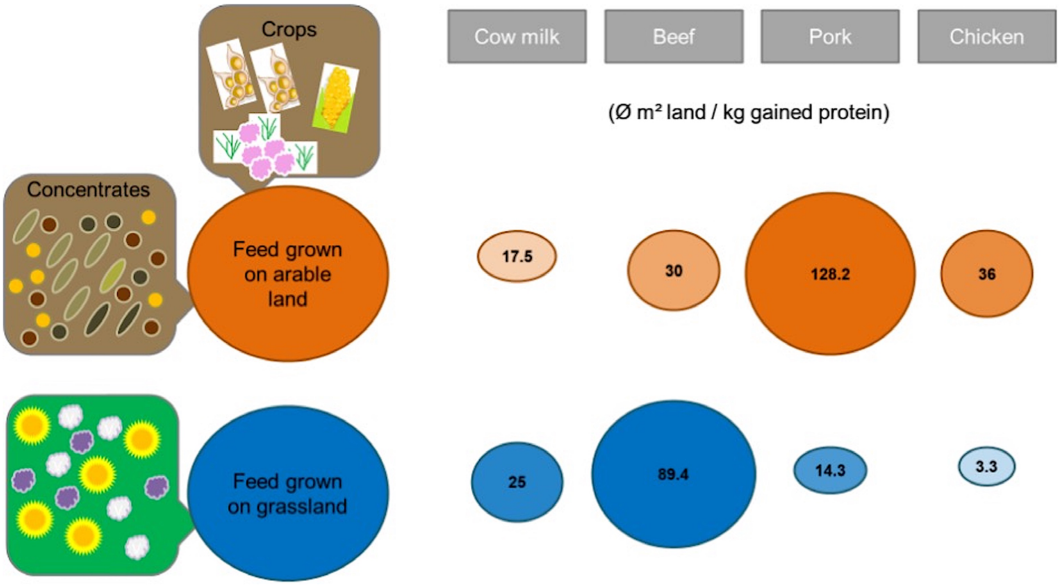

FIGURE 1 Arable land and grassland occupied for feeding livestock (m^2 of arable land and grassland area occupied for providing feed required by cows, cattle, pigs or chickens to gain 1 kg protein). Data are derived from Flachowsky, Meyer & Südekum (2017, *animals*).

sorghum. Soymeal is also an essential component in global pig and chicken feeding (Steinfeld et al., 2006). However, there is substantial variation among feeding systems and geographic regions. In some countries, for instance, Canada, Israel, Japan, Korea, and several European countries, grains and soymeal also strongly contribute to the feed intake of dairy cows (FAO, IDF, & IFCN, 2014). In many dairy systems in continental Europe, non-grazing and indoor management by feeding a total mixed ration composed of conserved forage (mainly grass and maize silage) and concentrates (Schingoethe, 2017) is common. In most dairy systems in Ireland and the UK, however as well as in New Zealand and Australian, grazing is predominant. For those grazing systems, amounts of silage and grain in the diet are generally low, but levels have been increased during recent years. Indoor management of dairy cows throughout the year reinforces grassland intensification by increased fertilization and frequent cutting. Feeding systems with a high proportion of maize- and grass-silage also depend on protein- and energy-rich soymeal or cereals to compensate for nutritional deficits (FAO, IDF, & IFCN, 2014).

3 | DEGRADATION IN SUSTAINABILITY OF GRAZING SYSTEMS

For decades, a combination of overgrazing and the conversion of grazing land to crop production has shifted many grassland communities towards the world's most endangered ecosystems (Blair et al., 2014). Recent studies estimated that 49% of the world's total grassland area has already been degraded (e.g., Gibbs & Salmon, 2015).

However, the declining global grazing trend is evident but it varies among spatial and temporal scales (see Table S1). More and more European countries have reduced grassland utilization by grazing livestock (van den Pol-van Dasselaar et al., 2020). European grasslands are often characterized by widespread abandonment of extensive livestock grazing management on semi-natural grasslands and rangeland, large-scale intensification through ploughing, sowing of a few highly productive species, and fertilization to supply both grazing and non-grazing cattle, with the associated loss of biodiversity and other ecosystem services (Leroy et al., 2018; Wilsey, 2018).

In Australia and New Zealand, rangelands are still highly important for livestock farming. Nevertheless, changes in grazing intensity and timing combined with changes in abiotic factors have degraded natural swards (Archer et al., 2017).

For the United States, the expansion of croplands before the 1990s and the large-scale reseeding and fertilization of former species-rich prairie grasslands have caused widespread loss of all prairie grassland types, with resulting high costs for wildlife (Lark, 2020). In addition, climate change and changes in grazing land management also reinforce their degradation (Archer & Stokes, 2000).

Several countries of the neotropical realm, for instance, Brazil and Argentina, have shown a distinct decline of the grazing land area within the total agricultural area during the last 15 years. Over 60% of the ancient, highly diverse Cerrado of southern Brazil has been lost through land-use intensification and abandonment (Andrade et al., 2015).

Although the overall grazing land area has not distinctly altered in several parts of Africa (Kenya, Namibia, South Africa) and Central Asia (China), overgrazing remains a major problem, and when combined with increasing drought events it leads to widespread desertification and losses of ecosystem services (Burrell et al., 2020; Zhang et al., 2018).

Degradation of grazing land is often a result of overexploitation, either through overgrazing or from the improvement of intensive silage production for non-grazing cattle (Hoque et al., 2022). However, the perspective of future grazing management worldwide must be to reduce trade-offs and to bring the different goals more in line with each other. At present there is a lack of knowledge regarding its achievement.

4 | INFORMATION GAPS FOR MINIMIZING TRADE-OFFS IN GRAZING MANAGEMENT

As hundreds of millions of people all over the world rely on grasslands for several values, grazing management is integrated into a value chain. The socio-economic demands and services of public interest associated with the value chain must therefore be considered. Despite their importance, grassland ecosystems are often underappreciated in both regional and global policy development (Bardgett et al., 2021) leading to information gaps on sustainable grazing management and further socio-economic changes that have consequences for the production goals and scope of awareness and commitment to grazing management at all levels of society. All these factors can lead to inefficiencies in grazing management and ecosystem service provision.

Altered socio-economic changes have led to widespread losses of knowledge about the whole systems context of grazing (e.g., Varga et al., 2020). Moreover, the general decline in grazing induced a lack of knowledge in techniques for balancing livestock feed demand with herbage availability and their inappropriate implementation in the farming practice. These techniques include the stocking method (continuous, rotational, strip stocking—the timing of rotations) and the grass production mode under grazing (forage species and their combination in mixtures, varieties, and fertilization). Grazing measures that are not well adapted to the local situation can adversely affect feed utilization, with feed losses and the failure to convert the metabolizable energy of herbage into animal performance, whether as energy for maintenance or animal production. Avoiding herbage losses requires a sound understanding of the interacting effects of the animals and the site-specific sward conditions. This enables a precise and fine-tuned adjustment of the stocking of grazing animals. Furthermore, information about herbage mass and growth rate, herbage quality, i.e., nutrient and energy concentration and their digestibility, the botanical composition of the sward, the amount of biological nitrogen fixation by legumes, or the occurrence of plant diseases (van den Pol-van Dasselaar et al., 2020) at high spatiotemporal resolution is often lacking. Information on all these aspects is essential for precise, efficient, and sustainable grazing.

Beyond livestock production, the efficient provision of highly important ecosystem services delivered from grazing is currently uncertain. Even if farmers invest high commitment to deliver stabilizing ecosystem services, their evaluation, control, documentation for authorities and appropriate remuneration are presently challenging. This is caused by missing tools for easy-to-handle documentation and traceability.

There is a need to increase farmers' control and confidence in grazing efforts at various levels. In recent years there has been considerable technological innovations in information acquisition of herbage availability, and in monitoring and controlling animal movement for more efficient and sustainable stocking of grazing animals. Nevertheless, the widespread implementation in current farming practices and the further development of grassland-based livestock production systems are still pending.

5 | PERSPECTIVES FOR LIVESTOCK SYSTEMS

5.1 | Challenges of sustainable grazing

Livestock grazing directly and indirectly affects plant community composition, soil parameters, and nutrient cycles in space and time (Wrage et al., 2011) by selective feeding behaviour of grazers (Lyseng et al., 2018), spatial variability in the deposition of dung and urine (Sitters & Olde Venterink, 2021), by trampling (Pulido et al., 2018), and seed dispersal by animals' coats or faeces (Rico et al., 2013).

These processes influence the differentiation of small-scale habitats and the species diversity and composition at the landscape scale (e.g., Socher et al., 2013). In turn, spatial heterogeneity of herbage species leads to less selective grazing and balances plant defoliation and restocking of nutrients (Dumont et al., 2012; Pontes-Prates et al., 2020). Achieving these well-balanced animal-grazing land interactions require precise and efficient grazing management, which involves precisely timed rotations of the grazing animals and precise information about herbage availability, sward structure, and botanical composition in space and time. For sustainable and timely precise stocking of grazing animals across the farmland, the farmer needs to know the time when the canopy of the sward is at an ideal growth stage to be grazed, how much residual stubble to leave before moving the grazers to another paddock, how long it takes to use sward's canopy to the desired stubble height, and the actual stocking rate that allows quick recovery of the plants and uniform distribution of excreta for optimum forage quality. However, rapid advances in automated sensor technologies for monitoring and assessing sward conditions, monitoring and controlling animals' behaviour, movement, and forage intake, as well as current progress in information technologies for setting up data-driven decision support tools all have potential to support sustainable grazing by providing sophisticated knowledge, confidence and control of grazing (Table 1 and Figure 2).

5.2 | Tools for measuring herbage availability on pastures

Reliably accurate and precise knowledge of herbage quantity and quality on the pastures is vital for matching the demands of animal feeding. Thus, measuring the available herbage on pasture is the most important task in grazing management and determines the achievement of sustainable allocation of animal stocking rates to a certain pasture area for a certain amount of time (López-Díaz et al., 2011). Regular measurements of herbage availability on the entire farm help ensure an adequate herbage supply throughout the grazing season and help identify surplus herbage and poor-performing and

TABLE 1 Technological developments in information acquisition, processing, and management for spatiotemporal precise monitoring of grazing animals and adjustment of grazing allocation and their potential for improving grazing systems.

Domain	Parameter	Sensor/technology/tool	Commercially available sensor/tools examples	Information for farmers	Reference
Sward	Herbage mass	Clipping quadrats Sward stick Rising plate meter Handheld or vehicle-mounted devices with ultrasonic distance sensors Handheld or vehicle mounted spectral sensors in visible or near infrared light LiDAR on vehicles or drones Structure from Motion (SfM) or Mutli-View Stereopsis (MVS) algorithms	Platemeter (F400, Farmworks Precision Farming Systems Ltd., Feilding, New Zealand) Grasshopper (TrueNorth Technologies, Shannon, Ireland) GrassOmeter (Monford AG Systems Ltd., Dublin, Ireland) Portable HandySpec Field VIS/NIR, tec5, Germany Pasture Meter (C-Dax Agricultural Solutions, Palmerston North, New Zealand) GreenSeeker (Trimble Inc.) ASD FieldSpec3 spectroradiometer (Analytical, Spectral Devices) User-friendly computer programs for 3-dimensional scene reconstruction from aerial imagery	Assessing herbage growth rates, estimating animal performance in terms of milk and meat	Sanderson et al., 2001; Murphy et al., 2021; McSweeney et al., 2019 Moeckel et al., 2017; Fricke et al., 2011 Lussem et al., 2019; Moeckel et al., 2017; Fricke et al., 2011 Wijesingha et al., 2019; Cooper et al., 2017
	Herbage quality Vegetation composition and structure Identification of rare species/valuable habitats	Combination of various sensors (standard RGB, Multi- and hyperspectral sensors, laser scanning - LiDAR) on different plattforms	Various sensors available	Assessing feeding value, timing defoliation by adjusting management and allocation Identifying valuable habitat structures or single species Conservation by adjusting grazing allocation	Wachendorf et al., 2018; Atzberger, 2013
	Defoliation/land use dynamics	Near-infrared sensor, satellite based radar sensors	Sentinel-1/Sentinel-2 imagery analysis	optimizing timing and frequency of defoliation by adjusting allocation of grazing animals	Taravat et al., 2019
Grazing animal	Monitoring				
	Behaviour	accelerometer	CowManager (Agis Automatisiering BV, Harmelen, the Netherlands) MooMonitor+ (DairyMaster, Causeway, Co. Kerry, Ireland) CowScout (GEA, Zurich, Switzerland) Smartbow (Zoetis Services LLC)	Detecting oestrus and metabolic and digestive disorders from rumination activity and overall activity	Riaboff et al., 2022; Herlin et al., 2021; Duncan & Meyer, 2019; Ruuska et al., 2016; Ungar & Rutter, 2006
		accelerometer + pressure sensor	RumiWatch System (Itin and Hoch GmbH, Liestal, Switzerland)	Feeding behaviour, herbage intake estimation	

(Continues)

TABLE 1 (Continued)

Domain	Parameter	Sensor/technology/tool	Commercially available sensor/tools examples	Information for farmers	Reference
		Acoustic sensors	Hi-Tag (SCR Engineers Ltd., Netanya, Israel) and Qwes-HR (Lely Ltd., St. Neots, UK) IGER Behaviour Recorder System (Ultra Sound Advice, London, UK)	Detecting oestrus and metabolic and digestive disorders from rumination activity	
	Movement patterns	GPS logger pedometer	Various low cost GPS trackers available IceTag (IceRobotics, Edinburgh, Scotland)	Movement patterns; Diurnal patterns group dynamics grazing and pasture utilization patterns behaviour and health combined with accelerometers	Ungar et al., 2018 Liao et al., 2018; Schieltz et al., 2017; Harris et al., 2007; Beker et al., 2010; di Virgilio et al., 2018; Guo et al., 2009
	Physiology	Bolus	Tracking Bolus MK 3 eCow Ltd., UK smaXtex Bolus ph Plus smaXtec animal care GmbH, Austria	Body temperature and rumen pH: Assessing feed and water intake; detecting health disorders, changes in reproduction, heat stress; Detecting inadequate feeding by changes in pasture access and composition	Herlin et al., 2021
	Control				
	Movement and grazing behaviour	Automated gates	Grazeway, Lely Holding S.a.r.l., Maassluis, the Netherlands Batt-Latch Gate Release Timer, GrazeTech, West Ryde, Australia	control access of grazing animals to a certain pasture by pre-programmed times or remote control	Van Erp-van der Kooij & Rutter, 2020 Caja et al., 2020
		Virtual fencing	eShepherd (Agersens Pty Ltd.) Nofence© (Nofence, Norway) Halter (Auckland HQ, New Zealand) Vence® (Vence, California, USA)	Precise, dynamic and flexible control and adjustment of animals grazing allocation by moving the virtual borders through sending new coordinates to the GPS receiver unit at each animal's collar via Apps; GPS tracking; monitoring fence interactions and escapes (SMS notification); Flexible, context-depended grazing regimes	Aaser et al., 2022; Campbell et al., 2019, 2020; Lomax et al., 2019
		drones	Various commercial products available	Herding. Steering among paddocks	McDonnell & Torcivia, 2020; Brunberg et al., 2020

TABLE 1 (Continued)

Domain	Parameter	Sensor/technology/tool	Commercially available sensor/tools examples	Information for farmers	Reference
Decision support tools	Sward/herbage management	data-based online tool combining national census data with farming enterprise data	PastureBase Ireland www.pasturebaseireland.ie	Assessing herbage growth rate; appropriate pasture measurement and budgeting; increasing herbage intake and quality; better animal performance	Hanrahan et al., 2017
		online land cover analysis for Australian rangelands	VegMachine® https://vegmachine.net	Improved rangeland management and profitability	Beutel et al., 2019
	Cattle herd management software	*Beef cattle records management and performance analysis software*	Ranch Manager® https://www.ranchmanageropen.com CattlePro™ http://www.cattlepro.com	track and analyse animal and herd performance, calculate costs and amount of feed consumed, finance tracking	-

overexploited paddocks that require management decisions to maintain herbage quality (Hakl et al., 2012). Accurate estimation of herbage mass can be achieved through sward mass assessments at a specified cutting height from clipped quadrats, but this is labour- and time-consuming (López-Díaz et al., 2011). For timely management, herbage mass can be easily measured by simple techniques such as rising plate meters (RPMs) or more sophisticated spectroradiometers, which provide data to enable improved grazing management. RPMs measure the compressed sward height of the pasture (Sanderson et al., 2001). For precise information on how much herbage mass is available on-farm and how quickly the herbage stand is growing, the farmer walks across all paddocks taking up to 40 measurements of compressed sward height (CSH) per paddock at least once a week. Agricultural applications and forage species are considered to convert the CSH into kilograms of dry matter per hectare (kgDM/ha). Ensuring consistency of measurement of herbage available requires knowledge and considerable labour input by the farmer. Although RPMs are considered a sufficiently precise and efficient method for assessing herbage mass, numerous factors can affect reliability, determining large variation in dry matter contents within CSH measures (Murphy et al., 2021; Soder et al., 2006). One commercially available, sophisticated RPM with an associated micro-sonic sensor for accurate grass cover measurement is the Grasshopper (TrueNorth Technologies, Shannon), offered with an App and a large feature set for managing grazing on the farm (McSweeney et al., 2019). The built-in GPS feature enables farmers to map the entire farm. Moreover, the Allocation feature offers the farmer, based on the current CSH measurements on the paddocks and the animal number, decision support on where to place the strip fence. Precise information on spatiotemporal patterns of herbage mass is an important step towards yield optimization and sustainable nutrient balancing (Schellberg & Verbruggen, 2014). Compared to conventional data collection methods, sensors and IT-based methods that can automatically obtain relevant herbage mass and quality data and indicators for structural and functional heterogeneity of the sward with a high spatial and temporal resolution can enable precise and continuous grassland monitoring. Remote sensing is a promising tool for estimating dynamics in herbage availability and habitat structures, whereby small-scale heterogeneity and strong spatiotemporal dynamics in grassland systems challenge remote sensing techniques (Schmidtlein & Sassin, 2004). Low-cost and near-real-time remote sensing techniques are spectroradiometers such as GreenSeeker (Trimble Inc.), ASD FieldSpec3 (Analytical, Spectral Devices), and GeoSCOUT (Holland Scientific, Inc.). Such active optical reflectance sensors calculate the Normalized Difference Vegetation Index (NDVI) by measuring the canopy's reflectance between near-infrared and red light and estimating the herbage mass (Trotter, Lamb, Donald, & Schneider, 2010). As these sensors have integrated their light source, the light-emitting intensity is limited, and handheld or wheel-mounted measuring is required. Unmanned aerial vehicles (UAVs) are already used for grassland monitoring (e.g., Lopatin et al., 2017). UAVs have

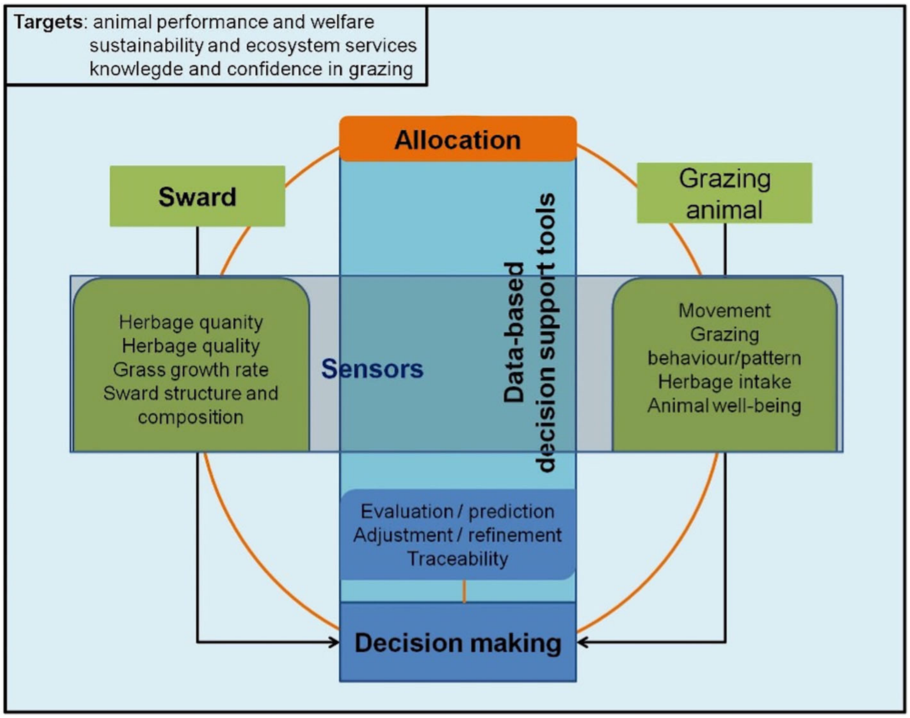

FIGURE 2 Domains for spatiotemporal precise monitoring of grazing animals and adjustment of grazing allocation.

hyperspectral cameras on board that produces spectral images of the grassland. Current research focuses on validating the UAV-based herbage mass and quality estimations for different grassland types and management regimes (cutting, grazing) by predictive modelling. Several studies have found strong predictive algorithms that provide the highest precision and accuracy between the spectral reflectance data from the UAV cameras and several vegetation parameters. Those correlations were found for measured canopy height, aboveground biomass (e.g., Zhang & Shao, 2021), forage yield (e.g., Lussem et al., 2018), crude protein, and acid detergent fibre (e.g., Wijesingha et al., 2020) from field surveys. These findings allow the generation of herbage maps that inform the spatial variation in herbage quality. Moreover, monitoring based on remote sensing (UAV, Sentinel satellite systems) equipped with visible light, spectral and hyperspectral, Lidar, or near-infrared sensors offers comprehensive information to support knowledge-based management decisions. Provided spectral data on herbage mass, herbage quality, and their dynamics allows for assessing herbage growth rates, potential animal performance in terms of milk and meat (e.g., Grüner et al., 2021; Hart et al., 2020), and optimizing timing and frequency of defoliation (Taravat et al., 2019) by adjustment of stocking grazing animals (Table 1).

However, the application of remote sensing is not yet widespread in grassland farming. A significant challenge for the practical use of sensor data as a basis for management decisions is the merging and processing of different data categories and data of different spatial and temporal scales. Further challenges remain in terms of improving the robustness of remote sensing techniques for estimating biomass and forage quality and inter-and intra-paddock variation. Furthermore, the widespread introduction of UAV platforms for grassland monitoring needs the development of cost-efficient UAV-based sensor systems (Bareth & Schellberg, 2018).

5.3 | Technologies for monitoring and controlling animal movement and allocation

Sophisticated grazing management requires the farmer to adjust and control precisely where the animals are, and to control when, what and how much they are grazing. The precise stocking of grazing animals across a farm's grazing area also implies there is control of animal movement and accessibility of specific paddocks or grazing strips at certain times.

There have been rapid advances in precision livestock farming (PLF) but technical innovations and commercialization are often restricted to indoor management, such as automated milking systems, walk-over-weighing systems and electronic cow identification and monitoring systems (Gargiulo et al., 2018; French et al., 2015). For intensive indoor dairy farming there are many commercially available sensors in terms of activity loggers for monitoring animals' location, behaviour, feed intake, milking, oestrus, and health status. These are summarized in Table 1. These monitoring tools contain accelerometers, pressure gauges and microphones. They are fitted to the animals by using ear-tags (e.g., CowManager), leg loggers (CowScout, IceTaq), collars (e.g., MooMonitor+) or internal boli (e.g., SMARTBOW) (Duncan & Meyer, 2019; Ruuska et al., 2016). Integrated GNSS receivers, accelerometers, activity, temperature and rumen sensors allow farmers to locate individual animals precisely, estimate for individual animals their eating and rumination activity and forage and water intake, help to detect oestrus, pH status of the rumen and feeding conditions, and also health problems (Herlin et al., 2021). Thus, for each animal in the herd, any small deviation from its normal behaviour can be quickly spotted by the farmer, often via SMS or smartphone Apps. However, validating such monitoring sensors for grazing is highly important for management decisions and remotely estimating animal performance and well-being.

Moreover, animal sensor systems allow remote detection of pasture conditions and composition changes by monitoring individual deviations in eating and ruminating behaviour or pH changes in the rumen. These sensors provide additional information to adjust pasture access and allocation of grazing animals. However, there have been rapid advances in tracking technologies for monitoring spatial behaviour of livestock due to the emergence of low-cost global navigation satellite systems (GNSS; Trotter, Lamb, Hinch, & Guppy, 2010). Equipping animals with GPS receiving collars enables detailed information about, for instance, movement patterns (Liao et al., 2018; Schieltz et al., 2017), group dynamics (Harris et al., 2007), grazing and pasture utilization patterns (Beker et al., 2010) and behaviour and health especially in combination with accelerometers (di Virgilio et al., 2018; Guo et al., 2009). Furthermore, drones with onboard cameras and rapid advances in image analysis techniques have great potential for monitoring and analysing animal behaviour (Rivas et al., 2018).

Drones also have enormous potential for use in herding animals. However, research on the response and surveillance of herding animals to flying drones is restricted to the recent studies by McDonnell and Torcivia (2020) and Brunberg et al. (2020). Technologies already exist to help control grazing access, including automated gates, e.g., Grazeway (Lely Holding S.a.r.l., Maassluis, the Netherlands) or Batt-Latch Gate Release Timer (GrazeTech, West Ryde, Australia). These automated gates can be used to control whether or not a dairy cow can access a specific pasture area by pre-programmed times or remote control and can be combined with robotic milking systems (Van Erp-van der Kooij & Rutter, 2020; Caja et al., 2020). However, these innovations may help by providing a technology to improve sustainable grazing but do not provide sufficient precision of control. Currently, control of grazing allocation is limited to labour-intensive and less flexible conventional fencing (Klootwijk et al., 2019).

Virtual fencing is a current innovation in digital tools for controlling animal allocation without setting any physical fence posts and wires. Virtual fencing can facilitate the implementation of productive and biodiversity-friendly grazing management regimes through a fine-tuned spatiotemporal control of animal movement and grazing behaviour (Anderson, 2007; Umstatter, 2011). Virtual fencing allows directing grazing animals at certain times to the most profitable paddocks and keeps them away from timely vulnerable habitat structures. The vision for controlling grazing animals' movement without setting less flexible, physical fences is not new. The first step towards this vision was the first description of a method and apparatus for controlling an animal by the patent of Peck (1973) approximately 50 years ago. Based on this patent, remote devices developed for training dogs, which are still commercially available under registered trademarks such as 'Invisible Fence,' were marketed, particularly in the USA. However, these first virtual fencing systems were not easy to handle. They required complex transmitter-receiver constructions and routines to determine the strength of radio signals depending on the animal's position within a specific area. Currently, developments for virtual fencing of livestock go beyond these first inventions. Now, virtual fencing combines positioning techniques (e.g., GPS) with a conditioned pre-warning stimulus and an aversive stimulus to prevent animals from crossing a virtually defined border. There is no physical, visible fence line/barrier. If the animal approaches the virtual border, the pre-warning, mostly acoustic stimulus, starts and increases in frequency and intensity the closer the animal moves towards the virtual border. If the animal does not respond to the pre-warning stimulus and fails to turn away from the virtual border, an aversive stimulus in the form of a weak and short-termed electric pulse is then given to the animal (e.g., Anderson et al., 2014).

However, at the time of writing, there were four upcoming start-ups worldwide developing and commercializing virtual fencing systems, but no widespread market release has been realized. Agersens (eShepherd, Australia), Nofence (Nofence, Norway), Vence (Vence, California), and Halter (Halter, New Zealand) develop VF systems that use a collar and transmit positional data via GPS. These VF systems should enable farmers to establish pasture boundary lines remotely using Apps on smartphones, tablets, or PCs. The centre of its technical invention and development and its extensive research and testing lies in Australia since the 2000s. In Europe, research and testing proceed more slowly, mainly driven by restrictions regarding the electric pulse application in the animal welfare acts and specific demands on animal testing. Currently, in most countries worldwide, the only way to try out VF is to get involved in Research and Development trials.

Nevertheless, the upcoming results in high efficiency in herding cattle in certain pasture areas, together with no obvious negative impacts on either animal behaviour and welfare, or on animal performance (i.e., no adverse effects on live weight gain) are therefore promising (e.g., Aaser et al., 2022; Campbell et al., 2019, 2020; Lomax et al., 2019). The agronomic and ecological benefits of VF for both intensive and extensive production systems still need to be assessed under different socio-economic and ecological conditions of dairy and beef cattle farms across different grazing systems. Nevertheless, its innovation might become a valuable tool for use in adjusting animal grazing in accordance with the spatiotemporal dynamics in herbage availability and habitat structures, flexibly and dynamically, by simply moving the virtual borders by sending new latitude and longitude coordinates to the GPS receiver unit at each animal's collar via smartphone Apps. Moreover, virtual fencing may reduce labour input resulting in higher time budgets for other economic activities and improve the work-life balance for farmers (Anderson, 2007; Lomax et al., 2019). VF might also be an opportunity for implementing grazing in formerly abandoned areas, protected habitats where physical fencing is prohibited (Monod et al., 2009), riparian areas (Campbell et al., 2019), moorland (Umstatter, 2011), or sites prone to soil erosion (Marini et al., 2018) or sites with potentially hazardous areas for animals such as cliffs, bogs, old mine shafts (personal communication Alan Hopkins). The potential of VF for timely and spatially precise grazing allocation is enormous. However, its economic viability and acceptance by authorities and the public still need to be proven and supported, and the boundaries for its correct use defined.

5.4 | Decision support tools for grazing and herd management

Although extensive data collection by sensor technology is already well developed, user-friendly tools that analyse data from different categories and extract useful information for management decisions are required. A range of different decision support systems and herd management software tools are already available in several countries. These tools assist farmers in assessing and visualizing the herbage availability on the farm, budgeting the herbage available, and managing stocking rates of their grazing cattle among the farm's paddock (Table 1). Decision support tools that facilitate on-farm management by visual representation of the herbage available on-farm have mostly been initiated in Australia, New Zealand and Ireland. These tools regularly use the farmer's weekly grass measurement data and combine long-term climate information, pasture, ground cover monitoring reports, soil erodibility data, satellite imagery and grass growth prediction models to deliver property-scale information on herbage availability. For instance, PastureBase Ireland is the Irish grassland database providing daily updates on grass growth across the country. It helps Irish dairy, beef, and sheep farmers to manage their grass production and utilization (Hanrahan et al., 2017).

Moreover, it contains several additional features, such as the Nitrogen Use Efficiency calculator and Nitrogen Planner for better nitrogen management. Furthermore, it integrates a Farm mapping tool to allow an easy way to profile the farm's grass supply as well as the MoSt GG model (Gilles grass growth model; Ruelle et al., 2018) to provide the farm's specific grass growth predictions at the paddock level according to weather, soil, and management data. For Ireland, seasonal and cost-effective proper management tools, such as the Spring Rotation Planner (SRP, Teagasc), exist. This tool helps farmers divide the farm's pasture area into weekly portions during spring, when the grass growth rate is typically lower than the cow's nutritional demands. However, its adoption in the Irish dairy sector is low (Hyland et al., 2018). VegMachine® is an online tool that uses satellite imagery to summarize decades of changes in Australia's grazing lands by processing long-term monitoring reports of ground cover, land cover change, and soil erosion rates (Beutel et al., 2019). This grazing tool is adjusted to field sizes standard for Australian dairy and beef farming.

Moreover, there are also livestock management software tools commercially available that assist farmers in managing, keeping track, and recording their livestock from birth to sale. Commercially available livestock management software such as Ranch Manager®, CattlePro®, and MiHub® help to manage and keep track of the number of animals on farm, ID and animals' location, pedigree, and breeding. These tools also support farmers in managing and recording due dates, treatments and sales. Furthermore, these software tools track and analyse animal and herd performance in terms of animal weight gains and identify top and bottom performers by simple visual representations, calculate the costs and amount of feed consumed by the animals, and thereby enable farmers to perform finance tracking of their livestock business.

All these available tools can help to understand the grazing land better, manage the stocking rate and better understand the impact of management decisions on herbage availability and animal performance. Nevertheless, few farmers use them for their daily business (Eastwood et al., 2019; Nuthall, 2012). This is likely because novel decision support tools have widely failed to convince the farmers of the economic advantages, the compatibility with their standard practices, and the manageable efforts for understanding, implementation, and management (e.g., Rogers, 2003). However, new ways should be explored to grassland farming better informed. Storing, processing, analysing, and visualizing agronomic grassland constitution data and animal stocking rates, forage intakes and animal performance all require software-based information management and decision support systems that can integrate data generated from various sources into the calculation of optimized grazing regimes in space and time (Sturm et al., 2018). Primarily, monitoring of ecological and agronomic information on grassland through remote sensing generates large amounts of data that must be compressed into easily understandable and manageable graphs and maps. To our knowledge, such a decision support system that optimizes stocking of grazing animals and agronomic and ecological outcomes by integrating and analysing multiple data at high spatial and temporal resolution does not exist at present, and it is not easily achievable. However, such tools will provide farmers with sufficient knowledge and assistance for sophisticated and sustainable grazing management within their production system and thereby increase their confidence in grazing management decisions. Moreover, as public goods in terms of ecosystem services delivered from grazing are not rewarded through market mechanisms (Leroy et al., 2018) and the demand for an entirely public-goods-oriented subsidy policy becoming increasingly prevalent in European society (e.g., Pe'Er et al., 2019), such decision support systems have also the potential to facilitate documentation, traceability, and certification of the production process for authorities and consumers (Franke et al., 2012). This is likely to improve the efficient provision of various ecosystem services.

6 | CONCLUSIONS

The rapid development of innovative farming technologies can enhance, improve, and take grazing management to the next level in the digital age. However, any new technology must be comprehensively tested and validated. Moreover, key technologies need to be integrated into an economically and ecologically viable system before making it widely available to farmers. No holistic system adequately integrates innovative technology in precision grazing livestock management and precision grassland monitoring into a system that can be used to monitor and manage all driving factors within the grazing system. As soon as these improvements in animal movement tracking and control technologies and remote sensing are integrated into a cost-effective system, there is a high potential to optimize the pasture utilization and improve the structural richness and biodiversity within the landscape (di Virgilio et al., 2018). For achieving holistic and knowledge-driven grazing management concepts that can enhance and sustain productivity, ecosystem services and animal welfare from grazing livestock farming, focusing on smart farming technology development and research, and knowledge transfer efforts involving all relevant grasslands stakeholders actors are essential. Innovative virtual fencing and remote sensing technologies are most promising for developing innovative grazing concepts that establish optimized and flexible spatiotemporal grazing patterns for cattle across the landscape. Furthermore, easy-to-handle decision support tools that integrate data from various sources for decision-making on the best grazing strategy under the actual farm's and grassland's constraints and enhance documentation, traceability, certification of production processes, and rewarding public goods are promising for optimized provision of various ecosystem services, as summarized in Figure 2.

Overall, holistic and knowledge-driven management concepts are likely to enhance and improve sustainable livestock grazing by giving confidence and control.

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CONFLICT OF INTEREST

All authors declare no conflicts of interest with the subject matter or materials discussed in this manuscript.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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