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The untapped potential of camera traps for farmland biodiversity monitoring: current practice and outstanding agroecological questions

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Abstract

Agroecosystems are experiencing a biodiversity crisis. Biodiversity monitoring is needed to inform conservation, but existing monitoring schemes lack standardisation and are biased towards birds, insects and plants. Automated monitoring techniques offer a promising solution, but while passive acoustic monitoring and remote sensing are increasingly used, the potential of camera traps (CTs) in farmland remains underexplored. We reviewed CT publications from the last 30 years and found only 59 articles that sampled farmland habitats in Europe. The main research topics addressed management or (avian) conservation issues, such as monitoring wildlife-livestock interactions, nest predation, and the use of feeders and water troughs. Fewer studies employed landscape-wide approaches to investigate species' habitat use or activity patterns over large agricultural areas. We discuss existing barriers to a more widespread use of CTs in farmland and suggest strategies to overcome them: boxed CTs tailored for small mammals, reptiles and amphibians, perch-mounted CTs for raptor monitoring and time-lapse imagery can help in overcoming the technical challenges of monitoring (small) elusive species in open habitats where misfires and missed detections are more frequent. Such approaches would also expand the taxonomic coverage of farmland monitoring schemes towards under-surveyed species and species groups. Moreover, the engagement of farmers in CT-based biodiversity monitoring programmes and advances in computer vision for image classification provide opportunities for low-cost, broad-scale and automated monitoring schemes. Research priorities that could be tackled through such CT applications include basic science topics such as unravelling animal space use in agricultural landscapes, and how this is influenced by varying agricultural practices. Management-related research priorities relate to crop damage and livestock predation by wildlife, disease transmission between wildlife and livestock, effects of agrochemicals on wildlife, and the monitoring and assessment of conservation measures. Altogether, CTs hold great, yet unexplored, potential to advance agroecological research.

Introduction

Agroecosystems cover about 44% of the Earth's habitable land (Food and Agriculture Organization of the United Nations, 2024) and have historically provided habitat for a large number of species (Jeanneret et al., 2021). In recent decades, agricultural intensification and landscape homogenisation have caused dramatic declines in individual abundance and species richness of plants (Wesche et al., 2012), insects (Raven & Wagner, 2021), birds (Rigal et al., 2023) and mammals (Browning et al., 2021; Smith et al., 2005). Monitoring the status and trends of farmland biodiversity is essential to inform and evaluate conservation actions to revert this trend (Geijzendorffer et al., 2016). Given the predominance of agroecosystems and the considerable financial, political and administrative efforts to manage them in a sustainable way, this is a global priority (Estrada-Carmona et al., 2022).

However, the cost of fieldwork campaigns, especially if performed by professionals, often sets a trade-off between available resources and comprehensive monitoring (Targetti et al., 2014). Recent technological advances now provide solutions for improved data acquisition and analysis (Besson et al., 2022). Passive monitoring techniques can abate the costs of fieldwork and expand the spatial and temporal span of monitoring efforts while also reducing human disturbance to wildlife during monitoring. For example, passive acoustic recorders like AudioMoths (Hill et al., 2019) and Batloggers (Adams et al., 2012) are becoming popular tools to monitor soniferous species like birds, bats, toads, frogs, crickets and grasshoppers (Sugai et al., 2019). Improvements in the spatial resolution of space- and airborne sensors have enabled their use for monitoring species richness and diversity of plants (Tay et al., 2018), and for counting individuals within wildlife aggregations (Lyons et al., 2019). For example, thermal cameras on drones were tested to reduce harvest-related mortalities of deer fawns and lapwings in agricultural fields (Cukor et al., 2019; Israel & Reinhard, 2017).

Camera traps (CTs) have become a widespread passive monitoring method in ecology and conservation due to their effectiveness compared to other monitoring methods (Wearn & Glover-Kapfer, 2019). CTs are particularly apt to monitor mammals, while they are also increasingly used in bird and herpetofauna studies (Burton et al., 2015; Delisle et al., 2021). However, unlike passive acoustic recorders and satellite-based remote sensing, which are becoming popular tools in agroecological research (Abdi et al., 2021; Müller et al., 2022; Vihervaara et al., 2017), also in respect to impact assessments of organic farming and other farmland-based conservation measures (Fialas et al., 2023; Markova-Nenova et al., 2023; Schöttker et al., 2023), CTs are still underutilised in agroecosystems. A recent global literature review of CT research found that only 16% of CT studies sampled anthropogenic habitats 'including urban or residential sites, farmland, pastureland, tree plantations, orchards, and cleared, or degraded tropical forest', whereas the vast majority of papers focused on forested ecosystems (Delisle et al., 2021).

In this manuscript, we focus on Europe as a case study, due to its long agricultural history and large share of agricultural land, which covers nearly half of Europe's terrestrial area (Ellis et al., 2021). The European Union (EU)'s expenditure towards farmland biodiversity conservation is one of the biggest nature conservation investments in the Old Continent (Batáry et al., 2015). This spending includes financial support for the establishment and maintenance of protected areas (Alliance Environnement, 2019), which cover a significant proportion of agricultural land in Europe (Vijay & Armsworth, 2021), and for the implementation of on-field conservation measures like eco-schemes and Agri-Environmental and Climate Measures (AECM) through the Common Agricultural Policy (CAP; European Commission, 2024). Despite this substantial spending for conservation, systematic monitoring of biodiversity throughout Europe is lacking (Moersberger et al., 2024; Vihervaara et al., 2023), thus preventing an accurate evaluation of conservation outcomes (Alliance Environnement, 2019). The majority of long-term biodiversity monitoring schemes at the national level exist to fulfil monitoring obligations of selected taxa (e.g. birds, butterflies) under European Directives, like the Habitats and Bird Directives (Moersberger et al., 2024). This produces a strong taxonomic bias in the monitored species, with birds being the best-monitored taxon in Europe, not only in farmland but also in other habitats. Apart from nationwide monitoring, a wealth of (often short-term, small-scale) farmland biodiversity monitoring data are collected as part of impact assessments of the CAP conservation measures, particularly AECM and organic farming. This data landscape is not only highly fragmented but also geographically and taxonomically biased (Ansell et al., 2016; Josefsson et al., 2020). Most AECM assessments have been carried out in intensively used agricultural landscapes of the United Kingdom, Sweden, France and Germany (Josefsson et al., 2020). Moreover, these studies have rarely focused on mammals, reptiles, amphibians and fishes (Ansell et al., 2016), creating an important knowledge gap. While CT-based monitoring efforts have increased in the present years, as is shown by continent-wide projects like Snapshot Europe (Wildlife Insights, 2024), agroecosystems appear to remain under-surveyed even in the framework of such large-scale projects.

In this paper, we review the application of CTs in European agroecosystems in the last 30 years. We discuss the reasons for the limited use of CTs in such environments and propose solutions. We argue that the full potential of CTs for biodiversity monitoring in agricultural landscapes has not yet been realised, and we propose unexplored CT use cases in this direction. Finally, we present some outstanding agroecological questions that could be addressed by CT applications.

Literature Review

We conducted a systematic literature search on Web of Science (www.webofscience.com) to assess the number and purpose of CT articles that sampled farmland. We focused on European agroecosystems and considered the following habitats as farmland: grasslands and pastures with livestock grazing, mowing or other management regimes; arable land (including fallows and flower strips); permanent crops for food production (e.g. orchards, vineyards, citrus and olive groves); abandoned (but still open) agricultural land; and landscape elements such as hedges, trees and woody biocorridors on farmland. We searched for articles that mentioned both CTs and farmland in their titles, abstracts, or keywords, using the following search string: ((‘camera trap*’ OR ‘infrared triggered camera*’ OR ‘trail camera*’ OR ‘automatic camera*’ OR ‘photo trap*’ OR ‘remote camera*’ OR ‘remotely triggered camera*’) AND (agricultur* OR farmland OR grassland* OR crop* OR arable OR pasture* OR orchard* OR ‘permanent crop*’)). The search was limited to articles written in English and published within the last 30 years, specifically between January 1,1994 and December 31, 2023. This initial search resulted in 640 articles (Table S1). We screened all articles to exclude those that did not describe original research (i.e. perspective, opinion and review articles), did not employ CTs, or did not focus on wildlife (e.g. lab experiments, experiments focused solely on captive animals, methodological advances in image processing or sensor development). We further restricted our analysis to articles whose study area was located in Europe, and which focused (also) on monitoring farmland habitats (i.e. either farmland was the main surveyed habitat, or at least one of the research questions was farmland-related). For these, we collated information on the surveyed species group(s) and on the study purpose, dividing the studies into six broad categories: basic science, faunal survey, conservation, management, methodology and trends (see Table S2 for a detailed description of each category). We also assigned a maximum of two research topics to each article (Table S3 lists all topics and their description) and assessed whether the study aimed to monitor biodiversity locally (i.e. at discrete sites or structures like nests, feeders, individual trees or flower strips) or at the farm (encompassing multiple fields or farms) or landscape (i.e. ‘a system of spatially arranged entities which are structurally and functionally interconnected’; Pereponova et al., 2023) level.

The Use of CTs in Farmland Biodiversity Monitoring over the Last 30 Years

Our literature review found only 59 articles that employed CTs for biodiversity monitoring in European farmlands, with the earliest article dated 2009 and an increasing number of articles published in more recent years (Table S1). Considering that CT research has boomed in the last decades (Delisle et al., 2021), this number is exceptionally low. The majority of studies were carried out in Spain, followed by the United Kingdom, Germany and Portugal (Fig. 1A). Mammals were the focal species in 32 articles, while 14 focused on birds, seven targeted both mammals and birds, one targeted birds and a reptile species (common adder *Vipera berus*), and the remaining five monitored the whole (vertebrate) species community. This confirms mammals as the most common target taxon in CT studies (Delisle et al., 2021), irrespective of the surveyed habitat.

Regarding the spatial scale of the studies, the majority of them monitored biodiversity at specific sites (n = 28), like (artificial) nests, feeders and water troughs, dung pats, carrion, flower strips or woodland corridors. There were 10 studies at the farm level and 21 studies at the landscape level, with the surveyed area ranging in size between 1.7 and 50,000 km^2, with varying spatial distribution of the CTs (e.g. subdivided across multiple sites or plots, evenly distributed, stratified by habitat or along environmental gradients) depending on the purpose of the study.

Most articles focused on management issues, such as the use of feeders and water troughs by domestic and wild animals, the effect of supplementary feeding on target and non-target species, the quantification of crop damage by wildlife and disease transmission via wildlife-livestock interactions and the exposure of wild species to pesticides or insecticides used in agriculture (Fig. 1B,C; Tables S2 and S3). Conservation was the second most recurring study purpose, with specific topics focusing mainly on nest predation of (often ground-nesting) birds, and on the habitat use and activity patterns of specific species of conservation concern, including invasive ones. Studies categorised as ‘basic science’ investigated topics such as habitat use and dietary selection, or other specific biological processes like resource transport (e.g. seed dispersal by birds) and scavenging. Methodological studies were few and included comparisons of CTs to other survey methods. Only one study performed a faunal survey, and only one investigated temporal trend in species abundance.

Reasons for a Limited Use of CTs in Farmland Biodiversity Monitoring

Discrepancy in the taxonomic focus of CT research and agroecological research in Europe

While CTs have been used predominantly for mammal monitoring, agroecology has traditionally focused mostly on birds, insects and plants, due to several factors. First, certain long-term farmland monitoring schemes exist to fulfil monitoring obligations of selected taxa (e.g. birds, butterflies) under the European Habitats and Bird Directives (Moersberger et al., 2024). Second, certain conservation interventions, like AECM, which have been the focus of much research, are designed to target specific species (typically birds, pollinators, or plants), which motivates the monitoring of these same taxa. Few AECM exist that target mammals, reptiles or amphibians: some examples include 'hamster-friendly' agricultural management (La Haye et al., 2020) and measures targeting certain bat species, water voles *Arvicola amphibius* and brown hares *Lepus europaeus* (MacDonald et al., 2019). The evaluation of such AECM relies on occurrence or abundance data of specific species, for which traditional field surveys, such as line transects, track and faeces counts, can be more cost- and time-efficient than CTs (Suárez-Tangil & Rodríguez, 2021; Valente et al., 2018).

Logistical and technical barriers in the design of CT studies in farmland habitats

While forests provide plenty of trees and logs on which to mount CTs, crop- and grasslands often lack natural vertical structures. Using poles or sticks is a simple solution, but one needs to consider that placing new poles may significantly alter the behaviour of certain species. For example, Kragten et al. (2008) suggested that poles used to mark nests of ground-nesting birds may attract predators. Poles can also constitute new perching spots for birds, thus attracting more and potentially novel avian species (see Hong et al., 2022 for an example of exploiting this perching behaviour as an advantage to enhance pest control while also monitoring avian communities in farmland).

The strongly structured nature of farmed landscapes, which are densely intersected by roads, water lines and field margins, also poses challenges in the setup of study

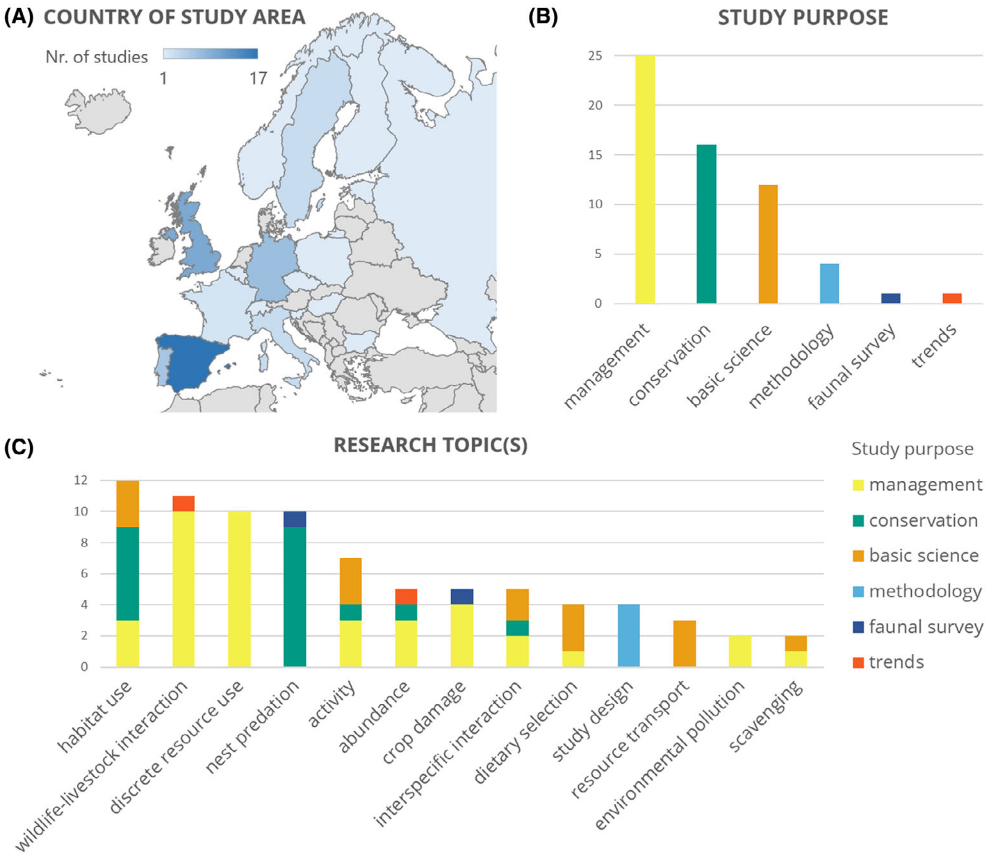

Figure 1. (A) Geographical distribution of the 59 articles using camera traps to survey farmland habitats, which were identified through the review. (B) Number of articles, divided by purpose of the study. (C) Number of articles for each research topic and by study purpose. Up to two research topics could be assigned to each article. A description of each study purpose and research topic, including the number of publications assigned to each of them, is available in Tables S2 and S3.

designs. Although this issue is not unique to farmed landscapes, we believe that it is exaggerated in this context. The animals' use of the landscape can be strongly influenced by such linear elements, and crop fields might be inaccessible for placing CTs. This is problematic in studies using metrics that assume random placement of the CTs across the landscape (Rich et al., 2019), and it complicates landscape-level inferences, as differences in detection probability for different linear features have to be corrected for (Kolowski & Forrester, 2017).

Once mounted, CTs with a passive-infrared sensor are more subject to misfiring and missed detections in open compared to closed habitats, due to denser ground vegetation and higher temperatures (Wearn & Glover-Kapfer, 2019). Furthermore, monitoring 'working landscapes' entails the risk of damage to CTs by farming operations (i.e. crop harvesting) or livestock. Certain farmlands may also be at a higher risk of vandalism or theft of CTs compared to other habitats with reduced human visitation rates and in which CTs are easier to camouflage or hide (Meek et al., 2019). Moreover, the fast growth of crops can obstruct camera views, requiring regular maintenance and adjustments to accommodate changes in the surrounding vegetation throughout the growing season.

Novel Applications and Opportunities for CT Use in Farmland

Boxed CTs to monitor small and elusive species

As highlighted above, few studies exist on mammals, amphibians and reptiles that use farmland as part of their habitat. Boxed CT systems have been recently developed to improve the monitoring of small animals (Hobbs & Brehme, 2017). Some of them tailor selected species (groups), like the *Mostela* for small mustelids (Mos & Hofmeester, 2020), the *DoMoS* for garden dormice *Eliomys quercinus* (Büchner et al., 2022), and the *campascope* for voles (Lisse & Pinot, 2024). Such devices could be deployed across different habitats to quantify the proportional use of farmland (relative to e.g. forests or urban areas) by the study species, or across farmed landscapes to study differential space use between crop types or management systems.

Time-lapse imagery

An unexplored avenue in CT research is the use of time-lapse, as opposed to motion-triggered, photography. This approach circumvents problems of misfires and missed detection which can affect detection rates in open habitats, and has been recently tested in arctic open landscapes (Leorna & Brinkman, 2024). Time-lapse imagery could be applied in the study of group-living animals that have been understudied in farmland so far, like deer, wild boars and geese. The technique could be used to monitor solitary animals too, for example, European badger *Meles meles*, red fox *Vulpes vulpes*, by using shorter time-lapse intervals, to minimise missed detections, and ideally using embedded systems, with computer vision capabilities integrated into cameras to process and interpret visual information directly on the device (Darras et al., 2024). This allows discarding empty images to reduce memory storage needs and speed up subsequent image classification.

Farmers' involvement in CT monitoring projects

Even if CTs can extend the time span of the monitoring and reduce the costs related to monitoring performed by professionals, the time investment necessary for CT deployment and regular swapping of batteries and memory cards can still be high. Involving citizens, landowners and land managers in CT projects can help abate such obstacles. In the UK, the portal *MammalWeb* enables country-wide collection and classification of CT data by citizen scientists, and its popularity has steadily grown (Hsing et al., 2022). Similar projects could be designed with farmers to monitor biodiversity on their land while contributing to a larger data pool for landscape-wide monitoring. Such an approach has been tested in France, where a citizen science programme including farmers encouraged invertebrate biodiversity monitoring of agricultural fields (Billaud et al., 2021). These programmes have additional benefits, like educating farmers about biodiversity of their land and building awareness about the importance of maintaining a balance between agricultural production and conservation.

Novel tools for efficient image processing

Technological advancements have significantly facilitated the collection of extensive CT datasets (Wearn & Glover-Kapfer, 2019). However, this abundance also presents challenges, as the vast amount of images, including those triggered erroneously by moving vegetation or rain, demands substantial time for manual review and annotation. Fortunately, deep learning tools, particularly those using computer vision, offer fast and reliable alternatives that drastically reduce processing times (Weinstein, 2018). The MegaDetector algorithm efficiently recognises and differentiates objects in images, identifying humans, vehicles, animals and empty frames (Beery et al., 2019; Tuia et al., 2022). Besides classifying species and behaviour (Norouzzadeh et al., 2018), recent research has developed models to estimate animal body size (Leorna et al., 2022). Density estimation, a common objective in wildlife monitoring for unmarked individuals, typically uses the random encounter model which requires data on the distance between the camera and the animal (Rowcliffe et al., 2008); a new model now automates this measurement (Johanns et al., 2022), saving significant time both in the field and during image processing. Additionally, extracting environmental data from images, such as vegetation phenology and snow cover, can now be automated (Breen et al., 2023; Sun et al., 2021).

Outstanding Agroecological Questions that CTs Could Answer

The field of agroecology could profit significantly from the CT applications listed above, helping to think beyond the borders of individual fields or farms and adopt a landscape-wide approach to farmland biodiversity monitoring. Here, we propose a non-exhaustive list of research priorities (accompanied by concrete examples; Fig. 2) in the field to improve our ecological understanding of agroecosystems and to inform and adapt farmland management. We also list the CT-derived metrics that would be suitable for each of these applications.

1. **Understanding effects of agricultural practices on animal occurrence and trends: how do different crop**

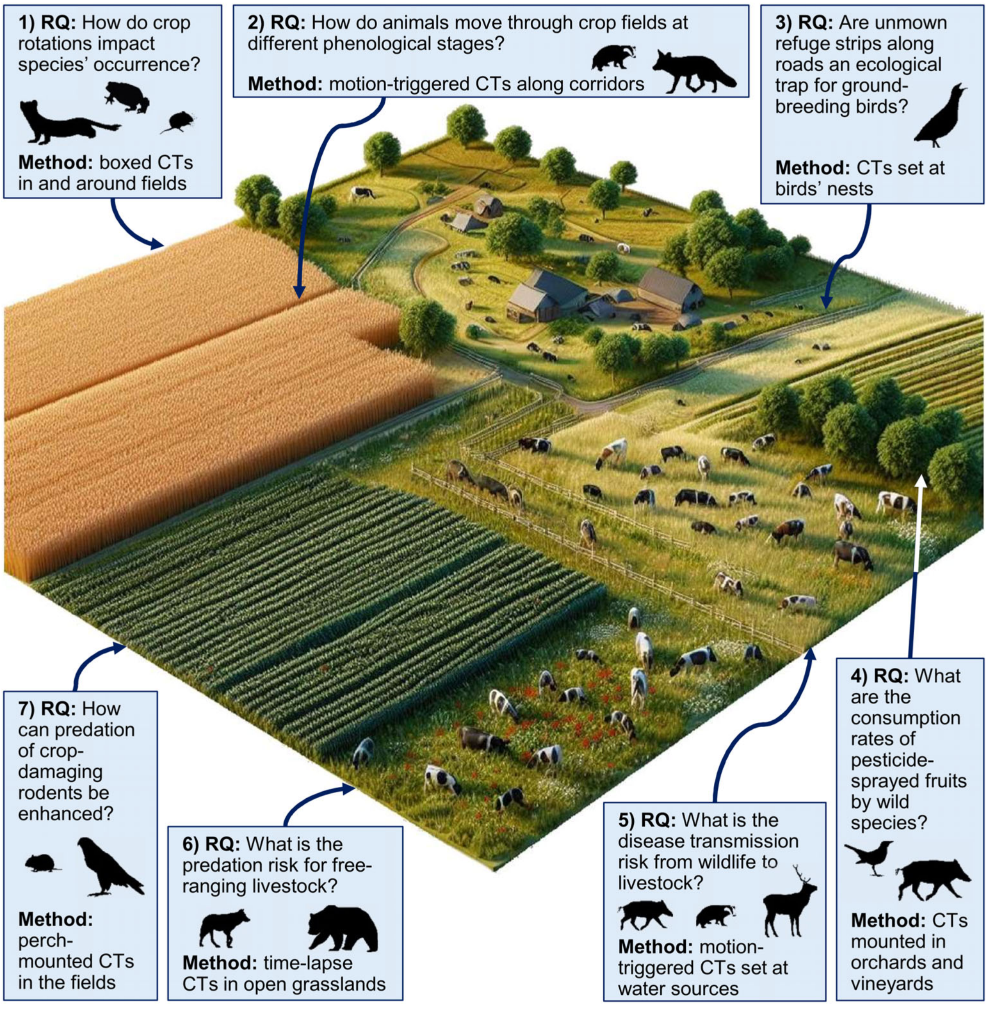

Figure 2. Outstanding agroecological research questions (RQ), with relative target species, which could be answered using camera traps (CTs). The questions are numbered in clockwise order, and the numbers relate to the bullet points in the section *Outstanding agroecological questions that CTs could answer* in the main text. The virtual landscape image was generated with Microsoft Copilot AI (copilot.microsoft.com); the species silhouettes were downloaded from PhyloPic (www.phylopic.org) version 2.0.

rotation, tillage and mowing regimes affect the occurrence and visitation rate of selected species? For example, the impacts of crop rotations have been studied in relation to soil microbial diversity (Venter et al., 2016) and to plant species (Koocheki et al., 2009), but knowledge gaps still exist on their effects on animals.

2. Exploring animal movement patterns in agricultural landscapes: do linear elements like field edges, flower strips and hedges increase landscape connectivity for certain species? How permeable are crop fields at different phenological stages? Effects of edge density, woody corridors and crop permeability have often been tested on pollinator or pest control species (Aviron et al., 2011, 2018; Martin et al., 2019), but less so on larger animals (but see Dvořáková et al., 2023; Pelletier-Guittier et al., 2020; Šálek et al., 2010). Visitation rates as derived from CTs can help close remaining knowledge gaps, especially when used in combination with telemetry data. Particularly, the integration of telemetry and CT data can improve abundance estimation (Chandler et al., 2022; Murphy et al., 2019), the quantification of landscape resistance, and the identification of (multispecies) movement corridors (Meyer et al., 2020). Such insights are important to maximise connectivity while minimising crop damage, making farmland more permeable.
3. Assessing the effectiveness of conservation actions: under which circumstances are certain AECM ecological traps? Studies have shown that flower strips next to roads can enhance car-related mortality of insects and birds (Senapathi et al., 2017) or alter predation rates of ground-nesting birds breeding within them (Hummel et al., 2017). Similarly, meadow bird reserves are subject to varying nest predation rates depending on bird densities and on the composition of the predator community (Frauendorf et al., 2022). This could entail some crucial spatial targeting implications for such conservation measures.
4. Effects of agrochemicals on animals: what is the exposure of wildlife to direct deposition, inhalation and consumption (through sprayed crops and fruits) of agrochemicals? What are agrochemicals' effects on the behaviour (feeding patterns, mating, nesting, etc.) and distribution of affected species? Little research has covered this topic so far (but see de Montaigu & Goulson, 2022; Lennon et al., 2020), though contamination by agrochemicals is being recognised as a growing environmental problem even further away from agricultural fields (Brühl et al., 2024). CTs set to monitor sprayed crop fields and orchards could be used to study visitation rates, as an approximation of exposure, by animals feeding on such fields. Time-to-event analysis could be used to estimate the timing of animals' occurrences relative to spraying events, as an approximation for exposure levels to the agrochemicals.
5. Interactions between wildlife and livestock in grazing systems: what are potential conflicts (besides predation) and how to minimise them? Can certain levels of livestock grazing be beneficial for wildlife species or communities? Resource competition between domestic and wild herbivores can be monitored via CTs, for example, by measuring visitation rates. Counteracting disease transmission is also particularly relevant given the recent outbreaks of African swine fever in some European countries (Boklund et al., 2020). On the other hand, positive relationships between livestock grazing and, for example, lagomorphs and ground squirrels' abundance have sometimes been documented (Salvatori et al., 2022; Schieltz & Rubenstein, 2016), and should be further explored to assess what is the optimal grazing pressure level that wild communities can benefit from.
6. Quantifying livestock predation rates: what are the density and visitation rates of predator species to pastures? Which are effective preventive measures? With the recent recoveries of large carnivores' populations across Europe, this topic is of utmost relevance. Novel antipredator methods using CTs to monitor wolf and guardian dogs' activity have already been proposed and put to the test (Guadagno et al., 2023).
7. Understanding grazing dynamics by species causing crop damage: how do grazing patterns vary across different species and according to crop type, field stage, season, and weather conditions? Visitation rates from CTs can help us assess the dynamics of crop use by ungulates and large grazing birds such as cranes, geese and swans, as well as evaluate repellent methods (Robai et al., 2024; Widén et al., 2022). Boxed CTs can be used to monitor the occurrence and visitation rates of rodents and estimate the related crop damage risk.

Conclusions

CTs have become popular tools in wildlife monitoring, but their application in farmland habitats has been limited so far. We argue that the potential for CT use in farmlands is vast but yet untapped: advances in CT applications tailoring specific species and habitats, farmers' involvement in monitoring projects and computer vision workflows for efficient image processing allow us to overcome many technical barriers and abate the costs which may have hindered a more widespread use of CTs in farmland. Landscape-level studies with farmland as the main habitat type, which are still relatively rare, could be particularly useful in improving our understanding of agroecological processes and in informing management actions for a more wildlife-friendly agriculture.

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Author Contributions

Stephanie Roilo: Conceptualization; data curation; formal analysis; methodology; visualization; writing – original draft; writing – review and editing. **Tim R. Hofmeester:** Conceptualization; methodology; supervision; writing – review and editing. **Magali Frauendorf:** Writing – review and editing. **Anna Widén:** Writing – review and editing. **Anna F. Cord:** Conceptualization; methodology; resources; supervision; writing – review and editing.

Conflict of Interest

The authors declare no competing interest.

Data Availability Statement

All data is available in the supplementary files.

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Supporting Information

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

Table S1. Reference list of all articles included in the systematic review.
Table S2. Names and descriptions of the six study purposes used to categorise the articles included in the literature review.
Table S3. Names and descriptions of the research topics used to subdivide the articles included in the literature review.

