Will passive acoustic monitoring make result-based payments more attractive? A cost comparison with human observation for farmland bird monitoring

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Keywords: Performance-based payments, monitoring costs, PAM, ARU, AudioMoth, bird surveys, payments for ecosystem services, agri-environment schemes

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Abstract:

Result-based payments (RBPs) reward land users for conservation outcomes and are a promising alternative to standard payments, which are targeted at specific land use measures. A major barrier to the implementation of RBPs, particularly for the conservation of mobile species, is the substantial monitoring cost. Passive acoustic monitoring may offer promising opportunities for low-cost monitoring as an alternative to human observation. We develop a costing framework for comparing human observation and passive acoustic monitoring and apply it to a hypothetical RBP scheme for farmland bird conservation. We consider three different monitoring scenarios: daytime monitoring for the whinchat and the ortolan bunting, nighttime monitoring for the gray partridge and the common quail, and day-and-night monitoring for all four species. We also examine the effect of changes in relevant parameters (such as participating area, travel distance and required monitoring time) on the cost comparison. Our results show that passive acoustic monitoring is still more expensive than human observation for daytime monitoring. In contrast, passive acoustic monitoring has a cost advantage for nighttime as well as day-and-nighttime monitoring in all considered scenarios.

Keywords: Performance-based payments, monitoring costs, PAM, ARU, AudioMoth, bird surveys, payments for ecosystem services, agri-environment schemes

1. Introduction

Payments that incentivise land users to implement biodiversity-enhancing land use measures have become an important policy instrument for biodiversity conservation (Engel, 2016). However, these payments for land use measures have often been criticised for their lack of conservation success especially in Europe and the US, where they are often implemented as agri-environmental schemes (Batáry et al., 2015; Wätzold et al., 2016; Khanna et al., 2018). A promising alternative are result-based payments (RBPs; also called performance-based payments - Burton and Schwarz, 2013), where land users receive a payment not for conducting a land use measure but if a specific conservation outcome is achieved (e.g. the occurrence of an endangered plant species on their land) (Herzon et al., 2016).

RBPs provide several advantages over action-based payments. They are more ecologically effective as land users only receive a payment if the conservation outcome is actually achieved (Burton and Schwarz, 2013). RBPs are also cost-effective, as only land users with low conservation costs will implement conservation measures on their land, which implies low compensation payments are needed and - for given AES budgets - a high conservation outcome can be achieved (Wätzold and Drechsler, 2005). Moreover, they provide incentives for land users to identify and implement innovative and ecologically successful conservation measures, as this increases the likelihood of receiving a payment (Bartkowski et al., 2021).

RBPs also face some challenges such as the correct definition of result indicators (e.g. Pinto-Correia et al., 2022), the dependence of conservation outcome on collective action of land users (Allen et al., 2014; Zabel et al., 2014) and risk aversion of farmers (see Burton and Schwarz (2013) and Drechsler (2017) for details). However, often prohibitively high monitoring costs stand out as a major barrier for a widespread implementation of RBPs (Burton and Schwarz, 2013). In particular, monitoring mobile species is time consuming and therefore costly (Zabel et al., 2014). This largely explains why – with a few notable exceptions for large charismatic species, such as wolverines (*Gulo gulo*) and lynx (*Lynx lynx*) (Zabel and Holm-Müller, 2008) and Golden Eagle (*Aquila chrysaetos*) (Suvantola, 2013) – existing RBPs focus on plants as target species (e.g. de Sainte Marie, 2014; Dunford, 2016; Russi et al., 2016).

However, new monitoring technologies may offer opportunities for better and more comprehensive monitoring (Kühl et al., 2020; Schöttker et al., 2022, Wägele et al.; 2022). Recently, autonomous recording units have rapidly gained traction in ecology and conservation, where they are used to study animal behaviour and to monitor ecosystems and populations (Browning et al., 2017; Shonfield and Bayne, 2017; Ribeiro et al., 2017). In addition, Bota et al. (2022) found that acoustic monitoring can be a practical and reliable means of monitoring compensation schemes in human-wildlife conflicts, specifically in this study in relation to damages caused by bee-eaters to beekeepers. Given the non-invasive nature of data collection using acoustic sensors for a wide range of sonant species and over extended periods of time (Pérez-Granados and Traba, 2021), passive acoustic monitoring (hereafter referred to as acoustic monitoring for simplicity) provides several advantages over human observations in conventional monitoring schemes (Darras et al., 2019; Sugai et al., 2019). While current research focuses mainly on the technical aspects of acoustic monitoring (e.g. Darras et al., 2018), cost considerations are crucial when considering the application of monitoring approaches on a large scale.

To our knowledge, only Williams et al. (2018) and Darras et al. (2019) have included cost considerations in a comparison between acoustic monitoring and human observation. These two studies indicate a cost advantage of acoustic monitoring over human observation for monitoring rare species, but still too high costs for surveying an entire bird community. However, the recent development of low-cost autonomous recording units such as AudioMoths (Hill et al., 2019) questions this finding.

In this study, we address the opportunity presented by the development of low-cost recorders with a particular focus on RBPs as a conservation policy instrument from a cost-perspective. We use the example of AudioMoths and investigate whether they can be a way to reduce monitoring costs and thus increase the attractiveness of RBPs for mobile sonant species such as farmland birds. We first develop a transferable general costing framework for comparing human observation and acoustic monitoring in the context of RBPs, which can be applied in and adjusted to different contexts. Second, we briefly outline a hypothetical RBP scheme for the conservation of farmland birds in a hypothetical agricultural landscape and use cost data for the corresponding monitoring activities. We focus on farmland birds, because acoustic monitoring techniques are particularly advanced for this group (Darras et al., 2019; Kahl et al., 2019). Further, farmland bird species are often of high importance in the context of payments to farmers for conservation measures (Busch et al., 2020; Kamp et al., 2021; Staggenborg and Anthes, 2022). We then derive monitoring scenarios in terms of the species and areas to be monitored, which determine the number of audio devices and monitoring campaigns required. Based on this, we compare the costs of human observation with those of acoustic monitoring using AudioMoths in combination with machine learning for data analysis. Finally, we perform sensitivity analyses, taking into account the uncertainty of certain parameter values and also possible future developments. This allows us to identify key factors that determine the cost relationship between human observation and acoustic monitoring. Our results can inform decision- and policy-makers involved in RBP design and implementation (e.g. within the CAP framework or private RBP initiatives). Moreover, our costing framework provides a systematic structure for studies to investigate costs of acoustic monitoring for RPBs and with adequate modification for conservation in general.

2. Costing framework

Here we present a general framework for calculating the costs of human observation and acoustic monitoring in the context of RBPs, which can generally be adapted to other contexts and specifications (e.g. patch or transect configurations and different monitoring equipment).

2.1. General considerations

We consider a landscape where N parcels, each with area $a = b \cdot c$, with width b and length c, participate in a RBP scheme, such that the total area participating in the scheme is: $N \times a = A$. For both monitoring approaches, we assume an initial investment. In our case study this includes different technical equipment for the two monitoring methods considered: audio recorders and battery charger for acoustic monitoring; binoculars and Bluetooth speakers for gray partridge call-playback (Interreg North Sea Region Programme, 2022; Kasprzykowski and Goławski, 2009) for human observation. A computer is required for both monitoring methods, but given its ubiquitous presence in administrations, we do not include it in the calculations. Some small amounts of data storage will be required for both monitoring methods (e.g. for GIS data, maps, reports and pictures), which we ignore. The large amount of audio data that needs to be stored in acoustic monitoring is what can cause differences in data storage costs between the methods. Here, we approximate the costs of data storage in acoustic monitoring by assuming that a new hard disc is purchased each year to store the following year's monitoring data.

We also consider monitoring costs (labour costs for observation or for audio recorder deployment), planning costs (labour costs for preparation and planning of the monitoring campaigns), analysis costs (essentially labour costs for both methods) and travel costs (including costs per km travelled by car and travel time costs). For the calculation of travel costs, we define an average travel distance between plots d. In the case of acoustic monitoring, there are also annual equipment costs (for replacing defective or missing audio recorders and for data storage). We assume that for both approaches, the monitoring of the RBP scheme is carried out by employees of a local administration.

We take into account that different costs occur at different points in time (recurring annual costs, but also one-time investment at the beginning of the RBP monitoring) through discounting. In economics, to account for time preferences of decision-makers (typically a preference for current over future income), discounting is applied to future cash flows, which results in lower present values of these future flows (e.g. Frederick et al., 2002). We use the real discount rate i and calculate the present values (PV) of costs for acoustic monitoring (AM) and respectively human observation (HO) $C^{AM/HO}$ incurred over the whole programme duration *T*=5 (typical for AES schemes) as:

$$C^{AM/HO} = \sum_{t=0}^{T} C^{AM/HO}\,(t) * (1+i)^{-t} \tag{1}$$

where $C^{AM/HO}(t)$ are the annual expenses incurred in year t, and t_0 stands for the beginning of the programme period of a RBP scheme when only the one-time investment $C^{AM/HO}(t=0)$ is incurred as costs. At the end of the program period (at *t*=*5*), the respective residual values of the one-time investments $RV^{AM/HO}(t=5)$ are included as negative costs (i.e. positive cash positions) in the calculation of the annual costs $C^{AM/HO}(t=5)$.

$$C^{AM/HO}(t=5) = C^{AM/HO}(t) - RV^{AM/HO}(t=5) \tag{2}$$

For both approaches in year t the total annual costs $C^{AM/HO}(t)$ are calculated as the sum of planning costs $C_P^{AM/HO}(t)$, monitoring costs $C_M^{AM/HO}(t)$, travel costs $C_T^{AM/HO}(t)$, analysis costs $C_A^{AM/HO}(t)$, and in the case of acoustic monitoring also equipment costs:

$$C^{AM/HO}(t) = C_P^{AM/HO}(t) + C_M^{AM/HO}(t) + C_T^{AM/HO}(t) + C_E^{AM}(t) + C_A^{AM/HO}(t) \tag{3}$$

2.2. Costs of human observation

Bluetooth speakers and professional binoculars (one for each observer) are the required one-time investments for human observation $C^{HO}(t=0)$. Since binoculars (with price p^{BI}) have an expected lifetime u_{BI} of 8 years (University of Regensburg, 2022) we include a residual value (based on straight-line depreciation) for them at the end of the 5-year program in the calculations. For speakers (with price p^{SP}), the residual value is considered and calculated in the same way:

$$RV^{HO}(t=5) = \frac{p^{BI}}{u_{BI}} * (u_{BI} - t) * n + \frac{p^{SP}}{u_{SP}} * (u_{SP} - t) * n \tag{4}$$

We assume that all tasks in human observation are conducted by ornithologists (academic staff) with hourly wage $w_O(t)$. For calculating the planning costs $C_P^{HO}(t)$ we consider a certain preparation and planning time in hours per ha (t_{prep}^{HO}):

$$C_P^{HO}(t) = w_O(t) * (t_{prep}^{HO} * A) \tag{5}$$

The monitoring costs are calculated as

$$C_M^{HO}(t) = w_O(t) * (t_{mon}^{HO} * A) * nc^{HO} \tag{6}$$

with t_{mon}^{HO} being the monitoring time spent on actual observation per ha, and nc^{HO} the number of monitoring campaigns (number of times the whole area has to be monitored) per year.

One monitoring campaign might require more than one consecutive observation of all plots, nr^{HO} being the number of travel rounds per ornithologist per campaign. Travel costs are calculated based on the travel time t_r^{HO} and travel distance s_r^{HO} per travel round to the observation area per ornithologist (over all ornithologists *n*) and the travel costs per km f.

$$C_T^{HO}(t) = n * w_O(t) * t_r^{HO} * nc^{HO} * nr^{HO} + n * f * s_r^{HO} * nc^{HO} * nr^{HO} \tag{7}$$

Analysis costs in human observation include the time for follow up analysis and organisation of the findings (t_{ana}^{HO}) and time for preparation of maps of breeding areas and a final report to document the results of the monitoring (t_{map}^{HO}).

$$C_A^{HO}(t) = w_O(t) * (t_{ana}^{HO} + t_{map}^{HO}) * A \qquad (8)$$

2.3. Costs of acoustic monitoring

Based on the number of audio recorders per plot AM^{AM} (given the generality of the framework, we use here the more general term audio recorder instead of AudioMoth) and the number of plots $\boldsymbol{N}$ the total number of recorders required for acoustic monitoring AM^{all} is calculated as:

$$AM^{all} = (AM^{AM} * \boldsymbol{N}) * \frac{1}{q} \; (q=1,\ 2,\ 3, \ldots) \qquad (9)$$

where $1/q$ indicates the fraction of plots that are monitored simultaneously. If all participating plots are monitored simultaneously (q=1), this requires purchasing audio recorders for all plots. If, for example, q=2, only half of the plots are monitored initially and then the audio recorders are removed and deployed on the rest of the plots, which saves part of the initial investment in audio recorders.

The one-time investment for acoustic monitoring $C^{AM}(t=0)$ includes the purchase of audio recorders, the related auxiliary equipment (memory cards and rechargeable batteries), external data storage, and a battery charger. Similarly to binoculars, audio recorders can in general be used longer than for 5 years. Therefore, we include a residual value (based on straight-line depreciation) at the end of the 5-year program in the calculations. We assume 6 years lifetime u_{AM} of audio recorders[1], and, considering also the yearly replacement rate of recorders due to theft or defects r^{AM}, we calculate a residual value for recorders at the end of the program period:

$$RV_{AM}^{AM}(t=5) = \sum_{t=1}^{4}\left[r^{AM}(t) * \frac{P^{AM}}{u_{AM}} * \frac{AM^{AM} \cdot N}{q} * (u_{AM} - t)\right] + \left(1 - 4r^{AM}(t)\right) * \frac{P^{AM}}{u_{AM}} * \frac{AM^{AM} \cdot N}{q} * (u_{AM} - t) \qquad (10)$$

where P^{AM} are the purchase costs of a recorder (including directly required equipment such as batteries and memory storage card). Replacement of recorders is assumed to take place at the end of the year (for $t=1,\ldots,4$), except when the scheme ends ($t=5$). Since the useful life time of a battery charger is 10 years[1] a residual value is calculated for it as well, similarly to equation 4.

In the case of acoustic monitoring, we assume that the monitoring is done by technical staff with hourly wage $w_T^{AM}(t)$ and the analysis (preparation of reports and verification of recordings) by academic staff with hourly wage $w_O(t)$. For preparation and planning, we assume a fixed time effort per monitoring campaign and ha t_{prep}^{AM} plus certain preparation time per recorder and campaign t_{prepAM}^{AM}. Thus, the planning costs equal:

$$C_P^{AM}(t) = w_T^{AM}(t) * (t_{prep}^{AM} * A + t_{prepAM}^{AM} * AM^{AM} * N) * nc^{AM} \qquad (11)$$

The monitoring costs depend largely on the number of audio recorders per plot AM^{AM}, the number of plots *N*, the time required to install and remove a recorder in the field ($t_{install}^{AM}$ and t_{remove}^{AM}), and on the number of monitoring campaigns nc^{AM}.

$$C_M^{AM}(t) = w_T^{AM}(t) * ((t_{install}^{AM} + t_{remove}^{AM}) * AM^{AM} * N) * nc^{AM} \qquad (12)$$

Travel costs are calculated similarly to human observation, by taking into account the travel time per travel round t_r^{AM}, the corresponding travel distance s_r^{AM} and the fact that two travel rounds are always required per campaign – one for deployment and one for removal of recorders (nr^{AM}=2). If only a part of the plots is monitored at the same time ($q>1$), consecutive monitoring is required which leads to a higher number of field trips per campaign ($nr^{AM} * q$).

$$C_T^{AM}(t) = n * w_T^{AM}(t) * (t_r^{AM} * nc^{AM} * nr^{AM} * q) + n * f * (s_r^{AM} * nc^{AM} * nr^{AM} * q) \qquad (13)$$

The equipment costs account for yearly replacement rate $r^{AM}(t)$ of defective or missing recorders and also for the battery charging costs *B*. Here, we also include the costs for data storage devices and assume that each year a new hard disc with price p_{SSD}^{AM} is purchased to store the next year's monitoring data. Thus, these costs occur in $t = 1$ to $t = 4$; the hard disc for year 1 is included in the one-time investment in $t = 0$.

$$C_E^{AM}(t) = r^{AM}(t) * P^{AM} * \frac{AM^{AM} \cdot N}{q} + B * nc^{AM} * AM^{AM} * N + p_{SSD}^{AM}, \quad for\ t = 1, \ldots, 4 \qquad (14)$$

$$C_E^{AM}(t = 5) = r^{AM}(t) * P^{AM} * \frac{AM^{AM} \cdot N}{q} + B * nc^{AM} * AM^{AM} * N \qquad (15)$$

The analysis costs for acoustic monitoring include, as for human observation, the time effort in h/ha for preparation of maps and final report (t_{map}^{AM}) and the time effort of the ornithologist/s for the verification of the bird recognition results per recorder per campaign (t_V^{AM}). Thereby, we assume that species presence has to be confirmed at least twice and with an interval of at least seven days per monitoring campaign (Südbeck et al. 2005).

$$C_A^{AM}(t) = w_O(t) * ((t_{map}^{AM}) * A + t_V^{AM} * AM^{AM} * N *nc^{AM}) \qquad (16)$$

3. Application of costing framework

3.1. Hypothetical case study

Our case study in the context of a hypothetical RBP scheme is inspired by our current research on habitat preferences and resource use of farmland birds using acoustic monitoring in the floodplain of the river Mulde in Saxony, Germany. The study area is largely characterised by grassland for grazing and is designated as a Natura 2000 Special Protection Area for birds (SMEKUL 2022). Thanks to this research, we have detailed knowledge of the process of acoustic monitoring, which is required as a basis for the cost assessment.

We assume that a land user can apply for a RBP with a square plot of size 4 ha (200 m x 200 m) so that an AudioMoth can be placed in the middle of the plot and thus cover only the land user's area. This assumption is consistent with the recommended spacing between audio recording units for bird monitoring of 250 m (Abrahams 2018) and the recommended spacing between routes for human observation of 100 m (Südbeck et al. 2005). Costs are always considered per 100 ha of investigation area, which is a reference value used as ecological area sample in standards for bird observation in Germany (BfN 2022). In the base case scenarios, we set the total participating area in the hypothetical RBP scheme to 100 ha. An overview of all cost parameters and their values is given in Table A.1 in the Appendix.

For our analysis, we assume that the participating grassland area is located between two points (base point and mid route point in Figure 1), and that we have a starting point for the observers, which is 30 km away from the base point from where the observations start. This somehow reflects a situation where a local or regional nature conservation administration is located in a provincial town and is responsible for the surrounding areas. We set 2 km as the average distance between each two plots and between the base point and its nearest two plots. Since the total participating area is fixed at 100 ha in the base case, the number of participating plots decreases as the size per plot increases, and so does the travel time between plots (due to the fixed average distance between each two plots). In the case of human observation, we assume that each one of two ornithologists covers half of the monitoring plots and the corresponding travel route (from the base point to the mid-route point).

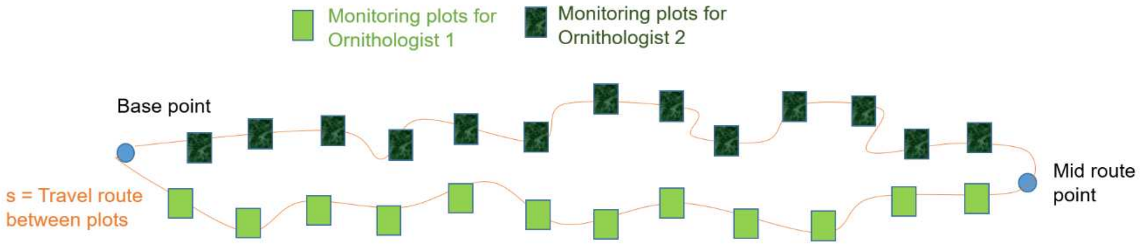

Figure 1 A hypothetical scenario for the participating area in a RBP scheme for bird conservation with plots distributed along two main roads. The different colors indicate how monitoring plots can be split between two ornithologists.

For our scenarios, we have selected a set of four farmland bird species that are of special concern in the context of agrobiodiversity decline (Busch et al., 2020; Kamp et al., 2020). We chose the whinchat (*Saxicola rubetra*) and the ortolan bunting (*Emberiza hortulana*) as diurnal farmland species that are both migratory and best surveyed in May and June (within the first six hours after sunrise). The gray partridge (*Perdix perdix*) and the common quail (*Coturnix coturnix*) were selected as species with nocturnal peaks of vocal activity that need to be monitored during a very narrow time window (at and shortly after sunset) in March and June, respectively (Südbeck et al., 2005). Given their different monitoring requirements this set of species allows us to compare the costs of the two monitoring approaches under three different scenarios: (1) *daytime monitoring* for the whinchat and ortolan bunting, (2) *nighttime monitoring* for the gray partridge (March) and common quail (June), and (3) *day-and-nighttime monitoring* for all four species. Given their importance for nature conservation, the selected species can be target species for a RBP scheme and farmers can improve their habitat conditions by establishing flowering areas, fallow strips, linear structures such as hedges (Laux et al., 2017; NLWKN, 2011), or avian-friendly mowing and grazing regimes (Johst et al., 2015).

Song activity of whinchat and ortolan bunting is mostly indicative for territory establishment and breeding, especially from early/mid-May to mid/late June (Südbeck et al., 2005). We can therefore define the confirmed presence of singing activity in May and June as evidence of an active territory. For the gray partridge, territorial males' vocal activity peaks between early March and early April, while for the common quail it occurs in early to mid-June (and again in July, Südbeck et al., 2005). For a bird to be considered as territorial in German bird monitoring schemes, it must be detected at least twice (at least seven days apart) at the same site during the breeding season (Südbeck et al., 2005). We consider this two-time detection as a sufficient indicator for breeding in both human observation and acoustic monitoring resulting in a RBP to the farmer. Based on the above considerations, we propose a preliminary schedule for the three monitoring scenarios in Table 1.

Table 1. Main scenarios and corresponding monitoring schedules for the hypothetical RBP scheme (base case).

Species monitoring scenarios	***Human observation schedule***	***Acoustic monitoring schedule***[a]
Daytime monitoring (whinchat & ortolan bunting)	Three campaigns with one day round each with two ornithologists (from mid-May until mid-June)	Two campaigns (one in May and one in June) each including two seven-day[b] rounds
Nighttime monitoring (gray partridge & common quail)	Four campaigns consisting of two rounds each with two ornithologists (two nights at least seven days apart in March (gray partridge) and two nights at least 7 days apart in June (common quail))	Two campaigns (one in March and one in June) each including two seven-day[b] monitoring rounds
Day+nighttime monitoring (all four species)	Three day rounds and same number of night rounds as for nighttime monitoring, except that one nighttime observation in June is done on one of the three days with daytime monitoring	Three campaigns each including two seven-day[b] monitoring rounds: One only nighttime-monitoring campaign in March; and two day-and-nighttime-monitoring campaigns: one in May and one mid/end of June

[a] Since acoustic monitoring in our scenarios results in a manageable time effort per day, we assume that only one ornithologist is involved in deploying the devices, whereas human observation is carried out by two ornithologists. [b] Seven-day round refers to the time the AudioMoths remain at the field during each monitoring round.

Daytime monitoring for the diurnal species could last up to 6 hours per day, from 5 to 11 a.m. (including observation and travel between plots) (Südbeck et al., 2005). For gray partridge and common quail, *nighttime monitoring* would be required, which could only last up to 1.5 hours per night (including observation and travel between plots) (Südbeck et al., 2005). This time restriction is especially important for human observation, as the observations have to be extended to more days/nights and/or more observers, depending on the size of the monitoring area and the travel time between plots. With a total monitoring area of 100 ha and the other assumptions made, the *nighttime* observations have to be divided between two ornithologists and two nights.

3.2. Sensitivity analysis

To gain a better understanding of the relative costs of the two monitoring approaches and the factors on which they depend, we conducted sensitivity analyses. For some parameters (discount rate, travel distance between plots, different replacement rates of AudioMoths per year due to damage from rain or theft, time spent in human observation per ha and deployment time of AudioMoths per plot), sensitivity analysis is straightforward. Here, the values of the respective parameters are changed to a lower or a higher value, while the remaining parameters are fixed at their base case values. However, the variation of other parameters leads to changes in related parameter, which requires some explanation. The numerical values of parameters for the sensitivity analysis are presented in Table 2.

Based on our field experience, we assume that one AudioMoth can cover up to 5 ha square-shaped participating area. The detection radius of audio recorders, however, depends on multiple factors, such as microphone quality (signal-to-noise ratio), day or night monitoring, open land or dense vegetation, species monitored etc. (Darras et al., 2016, 2020).

Thus, the *eligible plot area* influences the number of AudioMoths needed for a total participating area of 100 ha (larger plots lead to overall fewer recorders). With smaller plot area the number of plots per 100 ha and the total travel time between plots increases (as we keep the distance between plots fixed), which corresponds to simulating a more dispersed participating area. We also include a low, base case and high value for the *total participating area* in the RBP scheme by keeping the eligible plot size fixed at the base case value and halving or doubling the number of participating patches, as this influences the required number of AudioMoths and the monitoring and travel costs. The total number of AudioMoths purchased depends also on the *fraction of plots monitored simultaneously* ($1/q$) and therefore the value of q is also part of the sensitivity analysis.

In addition, we consider results by Turgeon et al. (2017) on microphone variability and degradation and calculate the costs of acoustic monitoring with a lower useful lifetime of three instead of six years for AudioMoths, although from our field experience, the devices can be used for more than three years.

We also account for potentially lower analysis costs in the future due to further development of machine learning for bird call recognition (Pérez-Granados, 2023) and a related decrease in the false positive rate of these methods, which would lead to lower verification effort by ornithologists (we consider one third less time for verification of recordings) and thus lower data *analysis costs*. As the technology continues to improve, we do not expect the cost of this parameter to increase in the future.

Table 2 Scenarios for sensitivity analysis.

Scenarios	***low***	***base case***	***high***
Discount rate			
Discount rate (*i*)	1%	3%	5%
Travel distance between plots (how scattered are plots)			
Travel distance between plots in km (*d*)	1	2	5[a]
Replacement rate of audio recorders			
Replacement rate in % per year (r^{AM})	2	5	15
Useful lifetime of audio recorders			
Useful lifetime in years (u_{AM})	3	6	
Observation time per ha/ Deployment time per plot			
Human observation: monitoring hours per ha (t^{HO}_{mon})	0.035	0.045	0.05[a]
Acoustic monitoring: time spent for deployment and removal ($t^{AM}_{install} + t^{AM}_{remove}$)	10 min + 5 min	15 min + 10 min	20 min + 15 min
Eligible plot area (→ number of plots and AudioMoths per 100 ha)			
Size of monitoring plots in ha (*a*)	2	4	5
Number of AudioMoths/ 100ha depends on the size of plots and the fraction of plots monitored simultaneously (1/*q*, here *q=2*).	(25)	(13)	(10)
Total participating area			
Size of total grassland area to be monitored in ha (*A*)	50	100	200[a]
Fraction of plots monitored simultaneously (→ number of AudioMoths per 100 ha)			
Fraction of plots monitored simultaneously (1/*q*)	1	1/ 2	1/3
Number of AM/ 100ha depends on the size of plots (here *a=4 ha*) and the fraction of plots monitored simultaneously.	(25)	(13)	(9)
Analysis costs for acoustic monitoring			
Analysis cost multiplier	0.67	1	

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[a] *The high-value scenarios for distance between plots, total participating area and monitoring time result in three rounds of human observation per nighttime-monitoring campaign with two ornithologists, while in the base and low cases only two night rounds are required. Since two ornithologists are required for human observation in the sensitivity analysis with smaller plots, we assume two ornithologists for all human observation scenarios for the sake of comparability.*

4. Results

4.1. Base case

We compare the base case for the three main scenarios in Figure 2. The costs of acoustic monitoring are higher than the costs of human observation only in the base case scenario for *daytime monitoring*, which requires the least human effort and only three trips to the field. In contrast, human observation is more expensive in the base case of *nighttime monitoring* and *day-and-nighttime monitoring*. This is mainly due to the higher travel costs and, in the *nighttime monitoring* scenario, also to the higher monitoring costs.

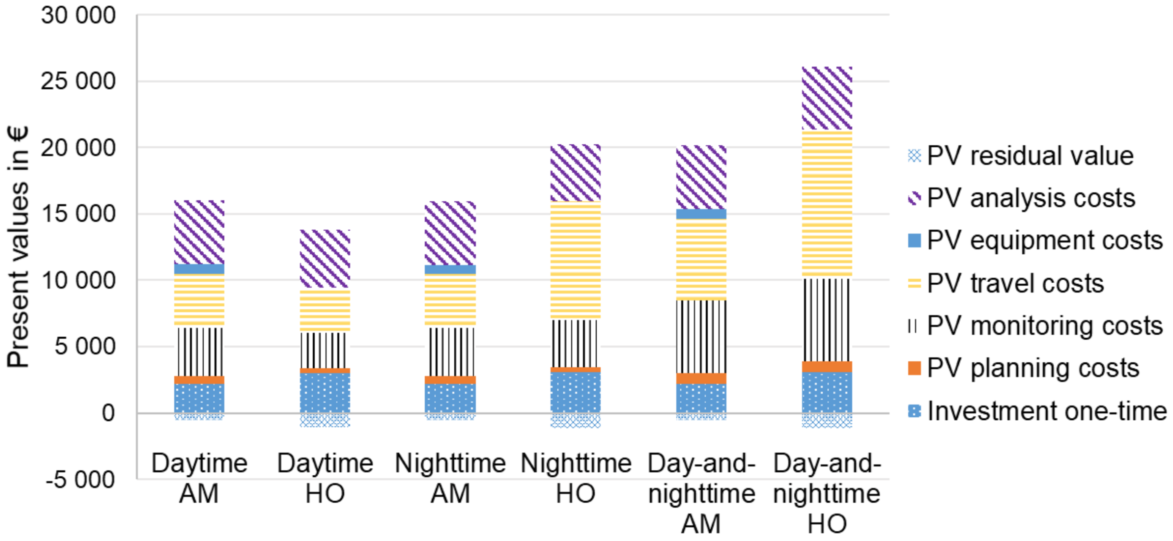

Figure 2 Comparison of discounted and aggregated costs of human observation (HO) and acoustic monitoring (AM) for the different scenarios using the base case values.

4.2. Sensitivity analyses

Human observation is always less costly in the *daytime monitoring* scenario, but always more costly in the *nighttime monitoring* and *day-and-nighttime monitoring* scenarios (Table A.2 in the Appendix). This is due to the short time window for *nighttime* observation, which requires more field trips, and/or more observers. In our base case scenario for *nighttime monitoring*, the number of field trips is the same for both methods (since acoustic monitoring is done simultaneously only on half of the plots), but acoustic monitoring has a cost advantage because it requires only one expert, whereas human observation requires two observers due to the restricted monitoring time window.

Assuming two times lower useful lifetime of recorders (i.e. three years) (which is similar to having two times higher price of recorders) as base value and using three instead of 6 years also in the sensitivity analyses does not change the cost comparison, except in the case of small monitoring plots (of 2 ha), where higher number of recorders are needed. Thus our results – from the base case and sensitivity analyses – are mostly generalizable also for recorders with twice lower useful lifetime (or respectively with twice higher price).

It turns out that for 100 ha participating area and 4 ha plots (our base case values), acoustic monitoring with simultaneous deployment of AudioMoths on all plots is less costly than monitoring only a fraction of the plots simultaneously in all monitoring scenarios (Table A. 3 in the Appendix), because the additional travel costs for deployment and removal outweigh the cost savings through lower investment in recorders.

An interesting insight is how the costs of the methods per ha monitoring area diverge based on the size of the area (Figure 3). For a smaller participating area of 50 ha, the cost difference between the two methods is rather similar for all scenarios. For a larger participating area of 200 ha, the cost advantage of acoustic monitoring in the night becomes more evident and *day-and-nighttime acoustic monitoring* becomes even less costly than *night observation*. We find that AudioMoths especially provide cost advantages when a RBP scheme involving *nighttime monitoring* or *day-and-nighttime monitoring* is to be implemented over larger areas. In these scenarios doubling the area covered from 100 ha to 200 ha leads to about more than 90% higher total monitoring costs (i.e. nearly constant cost per ha) for human observation due to the short time window for *nighttime* observation, whereas for acoustic monitoring the total costs increase only by about 60% (and the cost per ha declines by about 20%). This result suggests that acoustic monitoring can be more easily scaled up to cover a larger area compared to human observation. However, implementing RBPs with acoustic monitoring in a large region would still lead to high overall monitoring costs.

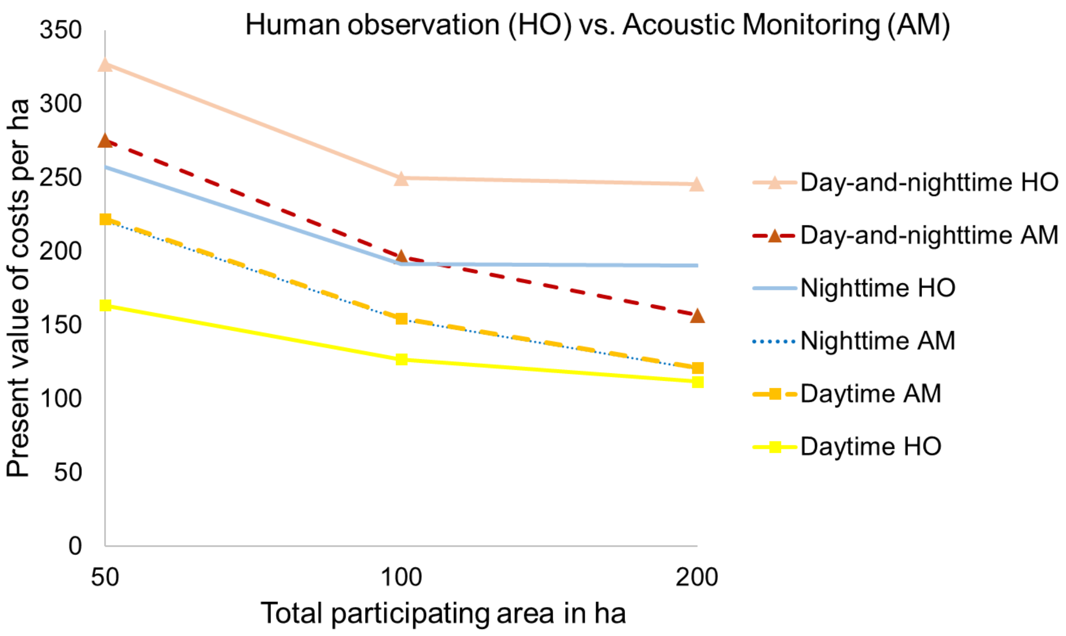

Figure 3 Present values of costs of human observation (HO) and acoustic monitoring (AM) per ha depending on the size of total participating area for all scenarios with base values.

Changing the discount rate to 1% or 5% has no significant effect on the cost comparison, since the present values change similarly for both methods. Varying the replacement rate of AudioMoths per year also results in only minor changes in cost, as does the future decrease in analysis costs due to technological development.

5. Discussion

While passive acoustic monitoring is increasingly applied in ecology and conservation, and more and more studies are being conducted on the topic, the idea of using it to facilitate monitoring in RBP schemes is new. This may be a way to reduce monitoring costs for mobile species such as birds, and make RBPs a promising alternative to payments for land-use measures for a wide range of species. To explore the cost-reducing potential of acoustic monitoring, we developed a general costing framework for acoustic monitoring versus human observation in the context of RBPs and applied it to a hypothetical RBP scheme. The proposed costing framework is quite general and can be applied by scientists and practitioners to assess costs of human observation and acoustic monitoring for other RBP schemes and – with adequate modifications – for conservation measures and policies in general. Naturally, the monitoring costs for both methods are context-dependent and for other species and conservation contexts other travel routes, detection radius of audio recorders, monitoring configurations and schedules might be required.

Our case study looked at human observation versus acoustic monitoring with AudioMoths for three monitoring scenarios for species with different vocal activity patterns (*daytime monitoring* for whinchat and ortolan bunting, *nighttime monitoring* for gray partridge and common quail, and *day-and-nighttime monitoring* for all four species). Thereby human observation was always less costly for *daytime monitoring*. By contrast, in the scenarios of *nighttime monitoring* and *day-and-nighttime monitoring*, which both include *nighttime* monitoring in a narrow time window and thus lead to a high human effort, acoustic monitoring had a cost advantage in all tested cases. Thus, acoustic monitoring may be beneficial when observing rare species that are difficult to detect and therefore require more field trips, such as the gray partridge.

As with all empirical cost assessments, our analysis contains uncertainties which we tried to capture with our sensitivity analyses. Moreover, we made some assumptions which may hold in some cases but not others. For example, we assumed that binoculars, speakers and audio recorders are used for our case study only. Under some circumstances, they may be used in multiple projects and how cost-effective their use is would depend on the number of projects. But since this consideration applies to both monitoring methods, we focus for consistency reasons on just one project – RBPs for farmland birds. Overall, we are confident that our main insights are robust to such type of assumptions.

Our results are consistent with the findings of earlier studies on costs of audio monitoring: Williams et al. (2018) show a general cost advantage and Pérez-Granados et al. (2018) a time saving advantage of acoustic monitoring over human observation for monitoring rare and patchily distributed bird species. Darras et al. (2019) confirm a cost advantage of acoustic monitoring for rare species and also for covering a large number of monitoring sites with only short monitoring time per site and a small number of audio recorders, but point to the higher costs of acoustic monitoring when surveying an entire bird community. However, they assume a high price for audio recorders and do not take into account residual values.

The findings of this research are directly relevant for policy makers who decide about the design of AES. Our results suggest that with the deployment of low-cost devices such as AudioMoths, the application of acoustic monitoring in RBP schemes becomes a policy-relevant option. Not only does this apply to single species, but AudioMoths could also enable a much larger number of target species to be covered in RBP schemes. Monitoring a larger set of target bird species with different breeding periods requires substantially more recurring visits under human surveys, resulting in higher costs. In contrast, depending on the duration over which audio recorders run cost increases are much more moderate with audio monitoring (AudioMoths have, in our experience, a battery life of about two weeks - for more precise estimates cf. Lapp et al. (2023)). Acoustic monitoring may also provide an opportunity to reduce the monitoring costs for other mobile sonant species such as bats, amphibians or certain insects, e.g. orthopterans, and thus enable RBPs to target such species. A general advantage of such large scale passive acoustic monitoring over longer periods is the generation of monitoring data which cover a whole soundscape and can be used for different analytical purposes beyond the implementation of RBP schemes. However, such large scale collection of data and their analyses would be more costly, despite the analysed cost advantages of acoustic monitoring over human monitoring.

A possible way to further reduce costs for acoustic monitoring could be to involve the land users (e.g. farmers) directly in the monitoring process, either by distributing audio recorders or microphones that can be connected to a smartphone, so that they can perform self-monitoring and forward the collected recordings to the RBP scheme administration. However, self-monitoring, as well as acoustic monitoring in RBPs in general, requires the farmers' acceptance of the use of acoustic monitoring in their fields and needs some mechanisms to ensure truthful reporting by farmers, which is both a topic for future research.

While the focus of our analysis was on costs, a current limitation for the practical implementation of acoustic monitoring in RBP schemes may also be legal restrictions associated with such applications. For data protection reasons, it would have to be ensured that human speech is automatically removed from the recordings before analysis. Moreover, there are currently also technical limitations for the implementation of passive acoustic monitoring in RPB schemes. The probability of malfunction of low-cost audio recorders deployed in the field needs to be further minimized. Currently, low-cost devices are also not able to provide feedback if they are not set up correctly, nor do they provide status reports on battery charge status. This lack of reporting capabilities could lead to prolongation of surveys after a malfunction has been detected or even prevent an assessment of the presence of a target species, which is, however, necessary for an RBP scheme. These possible problems or causes of errors can be minimised by deploying recorders that use wireless networks to send regular status reports so that potential intervention is possible during a survey rather than post-hoc. However, such devices would require higher investment costs and add further costs, e.g. for wireless network access. Our costing framework makes it easy to investigate such cost changes beyond the use of AudioMoths. For example, an additional analysis (data not shown) revealed that in our case study, even four or five times more expensive devices can still be more cost-effective than human observation at night.

We conclude that acoustic monitoring has enormous potential for the development of innovative RBP schemes for mobile species. Given the technological, logistical and administrative limitations we still face today, it will probably take some more time to realize the full potential of this approach. However, policy makers should monitor relevant technological, cost and societal developments and initiate pilot studies to prepare themselves for the implementation of RBP schemes that rely on passive acoustic monitoring to control the presence of target species. This could be one step in integrating biodiversity conservation concerns in the advancing digitalisation in agriculture and agricultural policy (Ehlers et al., 2022).

References

Abrahams, C. (2018). Bird bioacoustic surveys-developing a standard protocol. In Practice, (102), 20-23.

Allen, B., Hart, K., Radley, G., Tucker, G., Keenleyside, C., Oppermann, R., Underwood, E., Menadue, H., Poux, X., Beaufoy, G., Herzon, I., Povellato, A., Vanni, F., Pražan, J., Hudson, T., Yellachich, N. (2014). Biodiversity protection through results based remuneration of ecological achievement. Report Prepared for the European Commission, DG Environment, Contract No ENV.B.2/ETU/2013/0046, Institute for European Environmental Policy, London.

Bartkowski, B., Droste, N., Ließ, M., Sidemo-Holm, W., Weller, U., and Brady, M. V. (2021). Payments by modelled results: A novel design for agri-environmental schemes. Land Use Policy, 102, 105230.

Batáry, P., Dicks, L. V., Kleijn, D., and Sutherland, W. J. (2015). The role of agri-environment schemes in conservation and environmental management. Conservation Biology, 29(4), 1006-1016.

BfN. (2022). Federal Office for Nature Conservation. National monitoring center for biodiversity. https://www.monitoringzentrum.de/steckbriefe/oekologische-flaechenstichprobe-oefs. Last accessed: 02.12.2022.

Bota, G., Traba, J., Sarda-Palomera, F., Giralt, D., and Pérez-Granados, C. (2022). Passive acoustic monitoring for estimating human-wildlife conflicts: The case of bee-eaters and apiculture. Ecological Indicators, 142, 109158

Browning, E., Gibb, R., Glover-Kapfer, P., & Jones, K. E. (2017). Passive acoustic monitoring in ecology and conservation. WWF Conservation Technology Series 1(2). WWF-UK, Woking, United Kingdom.

Bünger, B., and Matthey, A. (2018). Methodenkonvention 3.0 zur Ermittlung von Umweltkosten. Methodische Grundlagen. Umweltbundesamt. Available at: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-11-12_methodenkonvention-3-0_methodische-grundlagen.pdf. Last accessed: 02.12.2022.

Burton, R.J.F., and Schwarz, G. (2013). Result-oriented agri-environmental schemes in Europe and their potential for promoting behavioural change. Land use policy, 30, 628–641.

Busch, M., Katzenberger, J., Trautmann, S., Gerlach, B., Droeschmeister, R., and Sudfeldt, C. (2020). Drivers of population change in common farmland birds in Germany. Bird Conservation International, 30(3), 335-354.

Darras, K., Pütz, P., Rembold, K., and Tscharntke, T. (2016). Measuring sound detection spaces for acoustic animal sampling and monitoring. Biological Conservation, 201, 29-37.

Darras, K., Batáry, P., Furnas, B., Celis-Murillo, A., Van Wilgenburg, S. L., Mulyani, Y. A., and Tscharntke, T. (2018). Comparing the sampling performance of sound recorders versus point counts in bird surveys: A meta-analysis. Journal of applied ecology, 55(6), 2575-2586.

Darras, K., Batáry, P., Furnas, B. J., Grass, I., Mulyani, Y. A., and Tscharntke, T. (2019). Autonomous sound recording outperforms human observation for sampling birds: a systematic map and user guide. Ecological Applications, 29(6), e01954.

Darras, K. F., Deppe, F., Fabian, Y., Kartono, A. P., Angulo, A., Kolbrek, B., ... and Prawiradilaga, D. M. (2020). High microphone signal-to-noise ratio enhances acoustic sampling of wildlife. PeerJ, 8, e9955.

de Sainte Marie, C. (2014). Rethinking agri-environmental schemes. A result-oriented approach to the management of species-rich grasslands in France. Journal of Environmental Planning and Management, 57(5), 704-719.

Destatis. (2022). Verdienste und Arbeitskosten – Reallohnindex und Nominallohnindex. 4. Vierteljahr 2021. (Earnings and labor costs - real wage index and nominal wage index. 4th quarter). https://www.destatis.de/DE/Themen/Arbeit/Verdienste/Realloehne-Nettoverdienste/Publikationen/Downloads-Realloehne-Nettoverdienste/reallohnindex-pdf-5623209.pdf;jsessionid=53274DD80D1A92024A421A70CCCFBF1A.live742?__blob=publicationFile. Last accessed: 02.12.2022.

Drechsler, M. (2017). Performance of input-and output-based payments for the conservation of mobile species. Ecological Economics, 134, 49-56.

Dunford, B. (2016). The Burren Life Programme: An overview [NESC Research Series Paper no. 9]. URL: http://burrenprogramme. com/wp-content/uploads/2019/10/NESC-Research_Series_Paper_9_BDunford_Burren. pdf. Last accessed: 02.12.2022.

Ehlers, M. H., Finger, R., El Benni, N., Gocht, A., Sørensen, C. A. G., Gusset, M., ... & Huber, R. (2022). Scenarios for European agricultural policymaking in the era of digitalisation. Agricultural Systems, 196, 103318.

Engel, S. (2016). The Devil in the Detail: A Practical Guide on Designing Payments for Environmental Services, International Review of Environmental and Resource Economics, *9*, 131-177.

Flade, M. (1994). Die Brutvogelgemeinschaften Mittel- und Norddeutschlands. Grundlagen für den Gebrauch vogelkundlicher Daten in der Landschaftsplanung. IHW-Verlag, Eching.

Frederick, S., Loewenstein, G., and O'donoghue, T. (2002). Time discounting and time preference: A critical review. Journal of economic literature, 40(2), 351-401.

Herzon, I., Birge, T., Allen, B., Povellato, A., Vanni, F., Hart, K., ... and Pražan, J. (2018). Time to look for evidence: Results-based approach to biodiversity conservation on farmland in Europe. Land use policy, 71, 347-354.

Hill, A. P., Prince, P., Snaddon, J. L., Doncaster, C. P., and Rogers, A. (2019). AudioMoth: A low-cost acoustic device for monitoring biodiversity and the environment. HardwareX, 6, e00073.

Interreg North Sea Region Programme. (2022, March 18). Volunteers make a difference in Burghsluis [Press release]. Retrieved from https://northsearegion.eu/partridge/press-releases/volunteers-make-a-difference-in-burghsluis/

Johst, K., Drechsler, M., Mewes, M., Sturm, A., and Wätzold, F. (2015). A novel modeling approach to evaluate the ecological effects of timing and location of grassland conservation measures, Biological Conservation, 182, 44-52.

Kahl, S., Stöter, F. R., Goëau, H., Glotin, H., Planque, R., Vellinga, W. P., and Joly, A. (2019, September). Overview of BirdCLEF 2019: large-scale bird recognition in soundscapes. In CLEF 2019-Conference and Labs of the Evaluation Forum (Vol. 2380, No. 256). CEUR.

Kamp, J., Frank, C., Trautmann, S., Busch, M., Dröschmeister, R., Flade, M., ... and Sudfeldt, C. (2021). Population trends of common breeding birds in Germany 1990–2018. Journal of Ornithology, 162(1), 1-15.

Kasprzykowski, Z., and Goławski, A. (2009). Does the use of playback affect the estimates of numbers of gray partridge Perdix perdix?. Wildlife Biology, 15(2), 123-128.

Khanna, M., Swinton, S. M., and Messer, K. D. (2018). Sustaining our natural resources in the face of increasing societal demands on agriculture: Directions for future research. Applied Economic Perspectives and Policy 40 (1), 38-59.

Kühl, H. S., Bowler, D. E., Bösch, L., Bruelheide, H., Dauber, J., Eichenberg, D., … and Herbinger, I. (2020). Effective biodiversity monitoring needs a culture of integration. One Earth, 3(4), 462-474.

Lapp, S., Stahlman, N., and Kitzes, J. (2023). A Quantitative Evaluation of the Performance of the Low-Cost AudioMoth Acoustic Recording Unit. Sensors, 23(11), 5254.

Laux, D., Herold, M., Bernshausen, F. and Hormann, M. (2017). Artenhilfskonzept Rebhuhn (Perdix perdix) in Hessen. Gutachten der Staatlichen Vogelschutzwarte für Hessen, Rheinland-Pfalz und Saarland. – Hungen.

NLWKN. (2011). Coastal Defence and Nature Conservation Agency Lower Saxony, Vollzugshinweise zum Schutz von Brutvogelarten in Niedersachsen (Implementation guidelines for the protection of breeding bird species in Lower Saxony), Status: 2011, https://www.nlwkn.niedersachsen.de/vollzugshinweise-arten-lebensraumtypen/vollzugshinweise-fuer-arten-und-lebensraumtypen-46103.html. Last accessed: 02.12.2022.

Pérez-Granados, C., Bustillo-De La Rosa, D., Gómez-Catasús, J., Barrero, A., Abril-Colón, I., & Traba, J. (2018). Autonomous recording units as effective tool for monitoring of the rare and patchily distributed Dupont's Lark Chersophilus duponti. Ardea, 106(2), 139-146.

Pérez-Granados, C., and Traba, J. (2021). Estimating bird density using passive acoustic monitoring: a review of methods and suggestions for further research. Ibis, 163(3), 765-783.

Pérez-Granados, C. (2023). BirdNET: applications, performance, pitfalls and future opportunities. Ibis.

Pinto-Correia, T., Ferraz-de-Oliveira, I., Guimarães, M. H., Sales-Baptista, E., Pinto-Cruz, C., Godinho, C., and Santos, R. (2022). Result-based payments as a tool to preserve the High Nature Value of complex silvo-pastoral systems: progress toward farm-based indicators. Ecology and Society, 27(1).

Ribeiro Jr, J. W., Sugai, L. S. M., & Campos-Cerqueira, M. (2017). Passive acoustic monitoring as a complementary strategy to assess biodiversity in the Brazilian Amazonia. Biodiversity and Conservation, 26(12), 2999-3002.

Russi, D., Margue, H., Oppermann, R., and Keenleyside, C. (2016). Result-based agri-environment measures: Market-based instruments, incentives or rewards? The case of Baden-Württemberg. Land Use Policy, 54, 69-77.

Schöttker, O., Hütt, C., Jauker, F., Witt, J., Bareth, G., and Wätzold, F. (2022). Monitoring costs of result-based payments for biodiversity conservation: Will UAV-based remote sensing be the game-changer? MPRA Paper No. 112942

Shonfield, J., and Bayne, E. (2017). Autonomous recording units in avian ecological research: current use and future applications. Avian Conservation and Ecology, 12(1).

SMEKUL. (2022). Saxon State Ministry of Energy, Climate protection, Environment and Agriculture. https://www.natura2000.sachsen.de/19-vereinigte-mulde-36573.html. Last accessed: 02.12.2022.

Staggenborg, J., and Anthes, N. (2022). Long-term fallows rate best among agri-environment scheme effects on farmland birds—A meta-analysis. Conservation Letters, 15(4), e12904.

Südbeck, P., Andretzke, H., Gedeon, K., Schikore, T., Schröder, K., Fischer, S., and Sudfeldt, C. (Eds.). (2005). Methodenstandards zur erfassung der Brutvögel Deutschlands. Max-Planck-Institut für Ornithologie. Vogelwarte Radolfzell.

Sugai, L. S. M., Silva, T. S. F., Ribeiro Jr, J. W., and Llusia, D. (2019). Terrestrial passive acoustic monitoring: review and perspectives. BioScience, 69(1), 15-25.

Suvantola, L. (2013). The Golden Eagle Compensation Scheme in Finland as an Example of Incentive Measures. In: Klenke, R., Ring, I., Kranz, A., Jepsen, N., Rauschmayer, F., Henle, K. (Eds.). Human - Wildlife Conflicts in Europe. Environmental Science and Engineering. Springer, Berlin, Heidelberg.

Turgeon, P., Van Wilgenburg, S., and Drake, K. (2017). Microphone variability and degradation: implications for monitoring programs employing autonomous recording units. Avian Conservation and Ecology, 12(1).

University of Greifswald. (2022). Calculation of personnel costs. https://www.uni-greifswald.de/storages/uni-greifswald/1_Universitaet/1.2_Organisation/1.2.6_Verwaltung/Dezernat_3/Referat_3.2_Drittmittel/Informationen_und_Hinweise/Hinweise_zur_Berechnung_der_Personalkosten_fuer_die_Antragskalkulation.pdf

University of Regensburg. (2022). Useful lifetime of devices. https://www.uni-regensburg.de/assets/forschung/forschungsfoerderung/dfg-schluessel_nutzungsdauer.pdf. Last accessed: 02.12.2022.

Wägele, J. W., Bodesheim, P., Bourlat, S. J., Denzler, J., Diepenbroek, M., Fonseca, V.G., and Wildermann, S. (2022). Towards a multisensor station for automated biodiversity monitoring. Basic and Applied Ecology (59), 105-138.

Wätzold, F., and Drechsler, M. (2005). Spatially uniform versus spatially heterogeneous compensation payments for biodiversity-enhancing land-use measures. Environmental and Resource Economics, 31(1), 73-93.

Wätzold, F., Drechsler, M., Johst, K., Mewes, M., and Sturm, A. (2016). A Novel, Spatiotemporally Explicit Ecological-Economic Modeling Procedure for the Design of Cost-Effective Agri-Environment Schemes to Conserve Biodiversity. American Journal of Agricultural Economics, 98(2), 489-512.

Williams, E. M., O'Donnell, C. F., and Armstrong, D. P. (2018). Cost-benefit analysis of acoustic recorders as a solution to sampling challenges experienced monitoring cryptic species. Ecology and evolution, 8(13), 6839-6848.

Zabel, A., and Holm-Müller, K. (2008). Conservation performance payments for carnivore conservation in Sweden. Conservation biology, 22(2), 247-251.

Zabel, A., Bostedt, G., & Engel, S. (2014). Performance payments for groups: the case of carnivore conservation in Northern Sweden. Environmental and Resource Economics, 59, 613-631.

Appendix A

Table A.1 Parameters in the costing framework for human observation versus acoustic monitoring (all assumptions for duration of campaigns and preparation are based on own experience, sources of other assumed values are found in the last column).

General parameters		**Base case value**	**Source/Note**
T	years of AES duration for present value calculation	5	AES in the EU normally last 5 years
R	discount rate for present value calculation	0.03	Bünger and Matthey (2018)
N	ornithologists/technicians involved in acoustic monitoring or human observation	2 in HO 1 in AM	
cp_L	labour cost multiplier (reflecting increase per year)	1.0089	based on the average increase in real wages by 0.89% in Germany since 2015 (Destatis 2022)
w_O	hourly wage for human observation and acoustic monitoring analysis personnel (ornithologist)	42.33 $\frac{€}{h}$	with Master education and after 3 years working in public administration (Entgeltgruppe 13, Stufe 3 for Germany: TV-L Stufen: https://www.oeffentlichen-dienst.de/tv-l.html). We use the full salary + yearly bonus + employer personnel costs (payroll taxes) as a basis for hourly wage calculation (see University of Greifswald (2022) for the full calculation of personnel costs). The basis for the salary amount is publicly available information on salaries in public administration: https://www.lsf.sachsen.de/entgelttabellen-4485.html
w_T^{AM}	hourly wage for deployment of AM (technical staff)	36.82 $\frac{€}{h}$	with Bachelor education and after 3 years working in public administration (Entgeltgruppe 10, Stufe 3 for Germany
A	total monitoring area in ha *(predefined)*	100 *ha*	ecological area sample in Germany, for better comparability
a	area in ha per plot	*4 ha*	matches area requirement of species, especially gray partridge (as in Flade 1994)
N	number of plots	$N \;\; = A/a$	varies with species scenarios
b	width of plot in m *(predefined)*	$200\,m$	100 m is the recommended distance between routes for human observation (Südbeck et al. 2005).
c	length of plots in m	$200\,m$	Sensitivity analysis with 100 m and 250 m.
f	travel costs per km car travel	$0.30\,\frac{€}{km}$	Federal Travel Expenses Act: http://www.gesetze-im-internet.de/brkg_2005/BJNR141810005.html
s_{SB}	travel distance for ornithologist from start to base in km	30 *km*	start is the place where ornithologist comes from/works, base is the nearest town to the observation area
t_{SB}	travel time for ornithologist to base	0.5 *h*	For travel between start and base and base and midpoint of route without parallel monitoring we assume 60 km/h
v_M	car travel velocity in km/h between monitoring plots	40 *km/h*	Some plots could possibly be reached easily by public roads and 60 km/h, other plots could only be reached off-road, e.g. with 20 km/h. Therefore we set as average velocity 40 km/h.
v_R	car travel velocity in km/h between start and base; base and midpoint route	60 *km/h*	For only travelling, without observation or AM deployment, we assume that public road network is used with 60 km/h.

General parameters		**Base case value**	**Source/Note**
$\boldsymbol{d}$	mean travel distance b/n each two plots and from base to plot 1 and plot N	$2\ km$	1 km and 5 km as sensitivity analysis
$\boldsymbol{s}$	total travel distance to reach all plots from base and back in km	$s\quad = d * (N + 1)$	varies with species scenarios
$\boldsymbol{t_{s60}}$	total travel time to reach all plots from base and back in h with 60 km/h	$t_{s60} = s\ \ /v_R$	varies with area scenarios
$\boldsymbol{t_{s40}}$	ts=Total travel time to reach all plots from base with mean area in h by car with 40 km/h	$t_{s40} = s\ \ /v_M$	varies with area scenarios (for simplification the length of the car route between the base and the midpoint is set identical to the length of the corresponding route between plots)
Human observation parameters only			
$\boldsymbol{nc^{HO}}$	number of observation campaigns	species scenario specific	assumptions based on Südbeck et al. 2005 (see section 3.1)
$\boldsymbol{nr^{HO}}$	number of observation rounds per campaign	species scenario specific	This value depends on the length of the travel route, the observed area and on the number of employees involved. With the assumptions made here, day campaigns with two observers are on one day, nighttime campaigns have to be on 2 or 3 nights (see section 3.1).
$\boldsymbol{t_{mon}^{HO}}$	time necessary to monitor a hectare of grassland by human observation (4.5h/100ha)	$0.045 \frac{h}{ha}$	based on own experience.
$\boldsymbol{t_{day}^{HO}}$	time available for observation and travel between plots per day	$6\ h$	from around 5:00 to 11 a.m., 6 h at most per day for monitoring and travel between plots (Südbeck et al. 2005)
$\boldsymbol{t_{night}^{HO}}$	time available for observation and travel between plots per night	$1.5\ h$	for nighttime observation only up to 1.5 h/ night around sunset (Südbeck et al. 2005)
$\boldsymbol{t_{prep}^{HO}}$	preparation time (2h/100ha)	$0.02 \frac{h}{ha}$	twice this value for day+nighttime monitoring assumed
$\boldsymbol{t_{ana}^{HO}}$	post processing and analysis time (2h/100ha)	$0.02 \frac{h}{ha}$	twice this value for day+nighttime monitoring assumed
$\boldsymbol{t_{map}^{HO}}$	time for follow-up and preparing the final report and maps	$0.2 \frac{h}{ha}$	(20 h/100ha)
$\boldsymbol{P_{aux}^{HO}}$	one-time costs for auxiliary equipment per 5 year AES	138 €	one-time every 5 years: a battery charger*78 EUR + an external 2TB SSD hard disc*60 EUR
$\boldsymbol{P^{BI}}$	purchase cost/price of binoculars	1500 €	https://www.astroshop.de/fernglaeser/20/m,ZEISS/a,Fernglaeser.Leistung.Vergroesserung=10-12?page=1
$\boldsymbol{u_{BI}}$	useful life time of binoculars	8 years	asset classification DFG, University of Regesburg https://www.uni-regensburg.de/assets/forschung/forschungsfoerderung/dfg-schluessel_nutzungsdauer.pdf
$\boldsymbol{P^{SP}}$	purchase price of bluetooth speakers	40 €	https://www.conrad.de/de/p/jbl-go-3-bluetooth-lautsprecher-wasserfest-staubfest-schwarz-2315258.html
$\boldsymbol{u_{SP}}$	useful life time of speakers	10 years	asset classification DFG, University of Regesburg https://www.uni-regensburg.de/assets/forschung/forschungsfoerderung/dfg-schluessel_nutzungsdauer.pdf

General parameters		Base case value	Source/Note
Acoustic monitoring parameters only			
$\boldsymbol{AM^{AM}}$	number of AM per plot	1	This number depends on the geometry of the plots and assumptions on the coverage radius of AM.
$\boldsymbol{q}$	number of rounds (q) per monitoring campaign depending on fraction (1/q) of plots monitored simultaneously	2	half of plots monitored simultaneously
$\boldsymbol{nc^{AM}}$	number of monitoring campaigns	species scenario specific	assumptions based on Südbeck et al. 2005 (see section 3.1)
$\boldsymbol{nr^{AM}}$	number of deployment travels to plots per campaign	2	Each campaign requires two travel rounds: one for installation and one for removal of AM.
$\boldsymbol{t^{AM}_{prep}}$	one-time preparation for deployment per campaign	$0.0033\ \frac{h}{ha}$	(20 min/100 ha)
$\boldsymbol{t^{AM}_{prepAM}}$	preparation time per AM and campaign	$0.05\ \frac{h}{AM}$	(3 min/AM, assuming personnel with some AudioMoth experience)
$\boldsymbol{t^{AM}_{install}}$	time for installation per AM	$0.25\ \frac{h}{AM}$	(15 min/AM)
$\boldsymbol{t^{AM}_{remove}}$	time for removal per AM	$0.17\ \frac{h}{AM}$	(10 min/AM)
$\boldsymbol{t^{AM}_{map}}$	time for follow-up and preparing the final report and maps	$0.2\ \frac{h}{ha}$	(20 h/100ha)
$\boldsymbol{t^{AM}_{V}}$	time needed by ornithologist for verification of recordings/ AM in h per campaign	$0.08\ \frac{h}{AM}$	(5 min/AM)
$\boldsymbol{r^{AM}(t)}$	replacement rate of AM per year	$5\frac{\%}{a}$	based on own experience
$\boldsymbol{B}$	battery costs per AM per campaign (15 days)	$0.0015\frac{€}{AM}$	(resulting from charging 3 AA batteries)
$\boldsymbol{u_{AM}}$	useful lifetime of AM	6 years	asset classification DFG, , University of Regesburg: https://www.uni-regensburg.de/assets/forschung/forschungsfoerderung/dfg-schluessel_nutzungsdauer.pdf
$\boldsymbol{p^{AM}_{SSD}}$	price of external SSD drive for data storage	species scenario specific	66 € for 2 TB for daytime monitoring; 47 € for 1 TB for nighttime monitoring and 80 € for 3 TB for day-and-nighttime monitoring (amazon.de)
$\boldsymbol{P^{AM}}$	**purchasing costs per AM + directly needed equipment in €, including:**	$159.31\ \frac{€}{AM}$	94 $ or 95 €/AM (10 pack) + 39.9$ or 40 €/ waterproof case + a microSD memory card of 64GB*17 € + 3*AA rechargeable Ni-Mh batteries*2.25€/battery (price sources given below)
$\boldsymbol{p^{AM}_{AM}}$	price of AM	$95\ \frac{€}{AM}$	www.labmaker.org, 22.09.22
$\boldsymbol{p^{AM}_{case}}$	price of waterproof case	$40\ \frac{€}{AM}$	www.labmaker.org, 22.09.22
$\boldsymbol{p^{AM}_{card}}$	price of microSD memory card 64GB	$17\ \frac{€}{AM}$	www.conrad.de, 22.09.22
$\boldsymbol{p^{AM}_{bat}}$	price of a AA rechargeable Ni-Mh battery	2.25 €	per AM three AA rechargeable Ni-Mh batteries needed (*2.25 €/battery - amazon.de, 22.09.22)

Table A.2 Results of the sensitivity analyses – present values in Euro.

	SCENARIOS					
Present values (PV) of costs for following sensitivity analyses:	**Daytime AM**	**Daytime HO**	**Nighttime AM**	**Nighttime HO**	**Day-and-nighttime AM**	**Day-and-nighttime HO**
PV - with t_{mon}^{HO} = 3.5h/ha in HO, compared with 5 min less for AM deployment and removal	14,001	**12,100**	***13,930***	18,364	***17,457***	23,583
PV - with t_{mon}^{HO} = 5h/ha in HO, compared with 5 min more for AM deployment and removal	16,918	**12,988**	***16,847***	20,231	***21,832***	26,652
PV - with a= 2 ha plots	24,060	**14,337**	***23,989***	24,770	***31,208***	32,211
PV - with a= 5 ha plots	13,537	**12,363**	***13,466***	17,509	***17,424***	23,485
PV - with a= 4 ha, q=2, with t_{mon}^{HO} = 4.5h/ha in HO - BASE CASE	15,459	**12,692**	***15,389***	19,153	***19,644***	24,963
PV - q=1, with all AM	15,358		***15,287***		***18,566***	
PV - q=3, with a third of AM	16,402		***16,331***		***21,356***	
PV - replacement rate r^{AM} = 2%	15,275		***15,205***		***19,460***	
PV - replacement rate r^{AM} = 15%	16,073		***16,002***		***20,258***	
PV – with useful lifetime of AudioMoths u_{AM}=3	16,859		***16,772***		***21,056***	
PV - 5 min/AM less deployment time	14,001		***13,930***		***17,457***	
PV - 5 min/AM more deployment time	16,918		***16,847***		***21,832***	
PV - Future technol progress: 33% less analysis costs	15,174		***15,104***		***19,360***	
PV - with A= 50 ha participating area	11,102	**8,172**	***11,031***	12,874	***13,777***	16,362
PV - with A= 200 ha participating area	24,174	**22,365**	***24,103***	38,027	***31,379***	49,162
PV - with d=1 distance between plots	14,430	**11,837**	***14,359***	16,930	***18,100***	22,120
PV - with d=5 distance between plots	19,374	**15,258**	***19,304***	27,533	***25,009***	35,710
PV – with discount rate i=0.01	16,274	**13,359**	***16,200***	20,165	***20,710***	26,324
PV - with discount rate i=0.05	14,715	**12,162**	***14,647***	18,230	***18,670***	23,721

Note: Values in bold type indicate that human observation is cheaper, whereas bold and italics means that acoustic monitoring has a cost advantage. If a cell is empty, then the sensitivity analysis influences only the costs of acoustic monitoring and the comparison should be to the costs of the base case human observation for the corresponding scenario.

Table A. 3 Results of the sensitivity analyses - present values as percentage changes to the base case values in each scenario.

	SCENARIOS					
Present values (PV) of costs for following sensitivity analyses as percentage change to base case value for AM and HO:	**Daytime AM**	**Daytime HO**	**Nighttime AM**	**Nighttime HO**	**Day-and-nighttime AM**	**Day-and-nighttime HO**
PV - with t_{mon}^{HO} = 3.5h/ha in HO, compared with 5 min less for AM deployment and removal	-9.4%	**-4.7%**	***-9.5%***	-4.1%	***-11.1%***	-5.5%
PV - with t_{mon}^{HO} = 5h/ha in HO, compared with 5 min more for AM deployment and removal	9.4%	**2.3%**	***9.5%***	5.6%	***11.1%***	6.8%
PV - with *a*= 2 ha plots	55.6%	**13.0%**	***55.9%***	29.3%	***58.9%***	29.0%
PV - with *a*= 5 ha plots	-12.4%	**-2.6%**	***-12.5%***	-8.6%	***-11.3%***	-5.9%
PV - with *a*= 4 ha, *q*=2, with t_{mon}^{HO} = 4.5h/ha in HO - BASE CASE	22%[a]	**100%**	***-20%*** [a]	100%	***-21%*** [a]	100%
PV - *q*=1, with all AM	-0.7%		***-0.7%***		***-5.5%***	
PV - *q*=3, with a third of AM	6.1%		***6.1%***		***8.7%***	
PV - replacement rate r^{AM} = 2%	-1.2%		***-1.2%***		***-0.9%***	
PV - replacement rate r^{AM} = 15%	4.0%		***4.0%***		***3.1%***	
PV – with useful lifetime of AudioMoths u_{AM}=3	9.1%		***9.0%***		***7.2%***	
PV - 5 min/AM less deployment time	-9.4%		***-9.5%***		***-11.1%***	
PV - 5 min/AM more deployment time	9.4%		***9.5%***		***11.1%***	
PV - Future technol progress: 33% less analysis costs	-1.8%		***-1.9%***		***-1.5%***	
PV - with *A*= 50 ha participating area	-28.2%	**-35.6%**	***-28.3%***	-32.8%	***-29.9%***	-34.5%
PV - with *A*= 200 ha participating area	56.4%	**76.2%**	***56.6%***	98.5%	***59.7%***	96.9%
PV - with *d*=1 distance between plots	-6.7%	**-6.7%**	***-6.7%***	-11.6%	***-7.9%***	-11.4%
PV - with *d*=5 distance between plots	25.3%	**20.2%**	***25.4%***	43.7%	***27.3%***	43.1%
PV – with discount rate *i*=0.01	5.3%	**5.3%**	***5.3%***	5.3%	***5.4%***	5.5%
PV - with discount rate *i*=0.05	-4.8%	**-4.2%**	***-4.8%***	-4.8%	***-5.0%***	-5.0%

Note: Values in bold type indicate that human observation is cheaper, whereas bold and italics means that acoustic monitoring has a cost advantage in the corresponding scenario. If a cell is empty, then the sensitivity analysis influences only the costs of acoustic monitoring and the comparison should be to the costs of the base case human observation for the corresponding scenario.

[a] *The base case cost values of acoustic monitoring are presented as percentage changes to the costs for the base case human observation.*