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Mitigating Wolf-Livestock Conflicts: Evaluating an Acoustic Anti-Predation Collar in Southern Italy

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Abstract

The recolonization of the wolf (*Canis lupus italicus*) in Italy represents conservation success, but it has led to increased conflicts with livestock farming. These conflicts may undermine traditional pastoral practices, which are important for maintaining rural landscapes and associated biodiversity. In 2023, the European wolf population exceeds 20,300 individuals, with an estimated 65,000 livestock losses reported annually across the EU. This study assesses the effectiveness of an acoustic anti-wolf collar to complement existing protective measures, including fencing, human surveillance, and guardian dogs. A field trial was conducted from June to August 2024 in the municipality of Bova Marina (RC), Italy, using three groups of 50 Aspromonte goats. The groups were managed by: (1) a shepherd only (PC), (2) a shepherd with guardian dogs (PGC), and (3) a shepherd with guardian dogs and the anti-wolf collar (PCGC). The collar emitting modulated frequency intervals based on natural harmonic sounds, intended to deter wolves, was mounted on goats. Monitoring, by camera traps, enabled a comparative analysis of predation events. The preliminary findings suggest that the use of the anti-wolf collar, may contribute to a reduction in predation and be a useful addition to strategies aimed at promoting coexistence between wolves and pastoral activities.

Keywords: goat predation; sheep predation; carcass decomposition; wildlife-livestock interactions; predator-prey-dynamics; forensic wildlife biology; livestock protection; ecological impact

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1. Introduction

In recent decades, the progressive recolonization of the wolf (*Canis lupus italicus*) along the Apennine and Pre-Alpine regions of Italy has been recognized as a conservation success. However, this recovery has also intensified conflicts with extensive and semi-extensive livestock farming systems, primarily due to increased predation on free-ranging livestock [1,2]. These interactions compromise not only the economic viability of livestock enterprises but also the resilience of local socio-ecological systems and the continuity of traditional pastoral practices, which are integral to the cultural identity and ecological integrity of mountain landscapes [3].

Extensive and semi-extensive livestock systems warrant protection, as they can contribute positively to biodiversity conservation when managed appropriately [4], and they hold substantial socio-cultural value [5]. Nevertheless, the demographic and spatial expansion of wolf populations has introduced new management challenges, particularly in relation to livestock protection and the development of effective coexistence strategies between large carnivores and rural communities [6].

Across Europe, the conservation status of the wolf has improved markedly, with population estimates rising from approximately 11,200 individuals in 2012 to over 20,300 in 2023—nearly doubling within a decade. This expansion has been accompanied by increased livestock predation, with an estimated 65,000 animals lost annually between 2020 and 2022 in EU member states [7]. Concurrently, the Italian sheep and goat sector has experienced a significant contraction, with a 20%

reduction in active farms between 2019 and 2023. By the end of 2023, the number of farms had declined to 112,385, reflecting the closure of nearly 20,000 operations within a single year [8].

Canis lupus is currently classified as vulnerable on the IUCN Red List (2023) [9], and its protection is supported by robust international and European legislative frameworks that recognize its critical ecological role [10]. The Bern Convention (1979) and CITES regulate habitat protection and wildlife trade, respectively [11,12]. At the European level, the Habitats Directive (92/43/EEC) [13] promotes the conservation of the species, while EU funding mechanisms—particularly the LIFE Programme—support concrete conservation and conflict mitigation initiatives [14,15].

Livestock protection can be achieved through sustainable and integrated strategies [16]. The most widely adopted methods include fencing, constant shepherd presence, and the use of guardian and herding dogs [17]. Fencing systems—whether fixed, mobile, electrified, or mixed—are particularly effective in critical contexts such as birthing periods or nighttime sheltering. However, their efficacy depends on regular maintenance to prevent breaches or technical failures [18].

Active shepherd surveillance remains one of the most effective deterrents against predation, allowing direct control over livestock. Yet, socio-economic changes and the historical absence of wolves have contributed to a decline in shepherd numbers, prompting increased reliance on guardian dogs [1,19,20]. Breeds such as the Maremma-Abruzzese Sheepdog are particularly effective when properly socialized with livestock from an early age and managed to maintain their protective instincts. Their deterrent effect is primarily behavioral—barking, scent-marking, and physical presence disrupt predatory behavior in wolves [21,22].

To expand the scientific understanding of predation mitigation, recent research has explored innovative repellent methods as complementary or alternative tools to traditional practices. Ethological theory distinguishes between primary and secondary anti-predator defenses [23,24]. Primary defenses are chronic and non-contingent, operating continuously without requiring immediate stimuli. These include behavioral, physiological, or morphological adaptations such as crypsis, nocturnality, or preference for sheltered habitats [25,26]. In contrast, secondary defenses are reactive and triggered by specific danger cues—such as predator odors, sounds, or movements—and include fleeing, freezing, heightened vigilance, or alarm vocalizations [27]. While effective, these responses often incur energetic costs and may interrupt essential activities like foraging or reproduction [24,28].

Applying this framework to wildlife management, Shivik et al. (2003) [29] categorized artificial deterrents into two main types: aversive stimuli (e.g., electronic collars) and behaviorally conditioned disruptive stimuli (e.g., acoustic and visual repellents). In a multi-species study involving wolves (*Canis lupus nubilus*), bald eagles (*Haliaeetus leucocephalus*), and bears (*Ursus spp*.) across six sites in Wisconsin, USA, behaviorally conditioned devices outperformed traditional deterrents such as electrified fladry—a rope or wire with fluttering fabric strips that create visual disturbance [30].

Many prey species (e.g., *Capreolus capreolus, Cervus elaphus, Dama dama*) exhibit behavioral and physiological adaptations for predator detection and avoidance, particularly through olfactory cues. Exposure to carnivore-derived substances (urine, feces, scent gland secretions, or fur) can suppress non-defensive behaviors (e.g., feeding, grooming) and prompt relocation to perceived safer areas—offering potential applications in agro-pastoral protection [27].

In the field of bioacoustics, Edgar et al. (2006) [31] tested ultrasonic deterrents on captive dingoes (*Canis lupus dingo*) but found no significant behavioral changes, underscoring the need for controlled, replicable trials. Similarly, Götz and Janik (2013) [32] evaluated Acoustic Deterrent Devices (ADDs) for protecting aquaculture from pinniped predation, identifying challenges such as habituation, environmental noise interference, and potential auditory harm to both target and non-target species.

In Europe, experimental efforts have led to the development of portable deterrent prototypes, including the anti-wolf collar patented by Pietro Orlando (Patent No. 202019000003221, issued 22/02/2022 by the Italian Ministry of Economic Development – Patent and Trademark Office). This solar-powered, durable acoustic device emits modulated frequencies and represents a promising innovation for reducing predation and fostering coexistence between humans and wildlife.

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Scientific literature increasingly supports the use of non-lethal technologies to mitigate conflicts between large carnivores and human activities, particularly in livestock farming [33,34]. A range of deterrents—acoustic, visual, electric, and chemical—have been tested with varying degrees of success depending on ecological and social context. However, the use of acoustic collars specifically targeting predators remains underexplored, especially in Mediterranean ecosystems [30].

Understanding species-specific auditory capabilities is crucial for designing effective acoustic deterrents. Wolves can detect a broad frequency range (approximately 40 Hz to 80 kHz), with heightened sensitivity between 40 and 80 kHz [35,36]. Domestic dogs (*Canis lupus familiaris*) perceive frequencies from 40 Hz to 60 kHz, with peak sensitivity between 1 and 20 kHz [37]. In contrast, livestock species have more limited auditory ranges—typically 250 Hz to 8 kHz—and reduced sensitivity above 20 kHz, though they can perceive sounds up to ~30 kHz [38,39].

These differences allow for the development of high-frequency acoustic signals that are perceptible and aversive to wolves but minimally disruptive to livestock and guardian dogs (Table 1). Such sensory insights are essential for creating targeted, non-lethal deterrents that reduce predation risk without compromising the welfare of domestic animals [36,39].

This frequency modulations based on natural harmonics deduced from ethnographic data, form psychoacoustic communicative signals for the wolf, which are the solution to drive the predator away from its prey as it enters the wolf's communicative language.

Table 1. Comparative Auditory Capabilities and Functional Adaptations in Wolves, Dogs, and Livestock: Implications for Acoustic-Based Management Strategies.

Feature / Parameter	Wolf (*Canis lupus*)	Dog (*Canis lupus familiaris*)	Livestock (sheep, goats, cattle, horses)
Hearing range (Hz)	~150–45,000 Hz (up to ~80,000 Hz in some sources) [36,40]	~67–45,000 Hz [37]	~23–40,000 Hz, depending on species [38,39]
Peak sensitivity (Hz)	~2,000–8,000 Hz (behaviorally); ~40,000–80,000 Hz (physiologically) [40]	~2,000–8,000 Hz (behaviorally); ~1,000–20,000 Hz [37]	~8,000–10,000 Hz (sheep/goats: ~10 kHz; cattle: ~8 kHz); ~1,000–8,000 Hz [38]
Ultrasound detection	Excellent; highly sensitive to ultrasonic range (up to 80 kHz) [36]	High; upper limit ~60 kHz [37]	Poor above ~20 kHz; limited response near 30–40 kHz [39]
Sensitivity level	Very high; adapted for long-distance detection and hunting	High, but variable across breed, age, and training	Moderate; suited to mid-frequency group alertness
Communication frequencies	~150–780 Hz (howls) with higher harmonics [41]	Wide repertoire: barking, whining, growling [37]	Mostly low-frequency vocalizations: bleats, moos, neighs [40]
Functional implication	Detection of prey, predators, and conspecific calls; social communication	Responsive to human cues and high-frequency commands	Adapted for herd alertness; limited reliance on high-frequency acoustic signals

Feature / Parameter	Wolf (*Canis lupus*)	Dog (*Canis lupus familiaris*)	Livestock (sheep, goats, cattle, horses)
Adaptation	Wild hunter: optimized for survival, navigation, and territorial vocalizations	Domestic adaptation: tuned to canine–human communication	Domesticated herd species: optimized for inter-individual contact and predator detection

2. Materials and Methods

2.1. Study Area

The field trial evaluating the effectiveness of the wolf deterrent collar was conducted from June to August 2024 at the Orlando Pietro farm, located in Contrada Vutumà, Bova Marina (Reggio Calabria), southern Italy, at an elevation of 200 meters above sea level (37°57′01″ N, 15°56′37″ E) [42]. This site lies within a designated disadvantaged area under national and European Union rural development frameworks and is situated in the hilly Mediterranean landscape of the Grecanic zone of Calabria [43]. The region experiences a typical Mediterranean climate, characterized by hot, arid summers and mild, wet winters. Annual average temperatures range from 9 °C to 31 °C, with mean annual precipitation of approximately 545 mm, predominantly occurring during the winter months. Seasonal variations in climatic parameters such as wind speed and relative humidity may influence the operational efficacy of acoustic deterrent systems (Appendix A, Table A1 for detailed climatic data).

2.2. Experimental Design

The trial was conducted on a cohort of 150 goats of Aspromonte (Capra dell'Aspromonte), an autochthonous breed well adapted to the mountainous and semi-arid environments of the southern Apennines, known for its hardiness and aptitude for extensive grazing. The animals were stratified into three homogeneous groups of 50 individuals each, balanced by age class—9 juveniles (<1 year), 10 primiparous and secondiparous (1–3 years), and 31 multiparous (>3 years); by sex (2 males and 48 females); and by physiological status—8 non-pregnant, 10 pregnant, and 30 lactating individuals [44]. This stratification was designed to control for potential behavioural and physiological variability that could influence experimental outcomes [45]. Each group was assigned to a separate 10-hectare paddock to ensure mutual isolation and was allowed to graze simultaneously during the months of June, July, and August 2024. Animal management adhered strictly to current animal welfare regulations, ensuring minimal stress. All individuals were identified in the National Database (B.D.N.) using ear tags and ruminal boluses registered to Azienda Agricola Orlando Pietro [46].

The three experimental groups were subjected to distinct grazing management strategies:

PC: Grazing under the supervision of an experienced herder only.

PCG: Grazing with an experienced herder and livestock guardian dogs (*Canis lupus familiaris*, Maremmano-Abruzzese breed), recognized for their effectiveness in predator deterrence (Gehring et al., 2010).

PCGC: Grazing with a herder, guardian dogs, and the application of an acoustic wolf-deterrent collar.

These management strategies were compared to evaluate their relative effectiveness in mitigating wolf predation, providing a basis for assessing the impact of integrated livestock protection measures.

2.3. Wolf-Deterrent Collar

The prototype wolf-deterrent collar (Figure 1) was developed using additive manufacturing (3D printing) techniques, employing a high-performance technical plastic filament characterized by elevated mechanical and thermal resistance. A wood-like coloration was selected for its low thermal conductivity, minimizing the risk of overheating under direct solar exposure. The collar was ergonomically designed through digital modelling to accommodate three primary functional components: (i) two piezoelectric speakers (POFET model, 30 Vp-p, 2.5 Hz–60 kHz), (ii) a Kemo M048N frequency generator module, adjustable between 7 and 40 kHz, capable of producing a maximum estimated sound pressure level of 110 dB at a distance of 1 meter, and (iii) a 12V (1.5 W) photovoltaic panel connected to a 150 Ah rechargeable lithium-ion battery. This configuration ensures operational autonomy for up to four days in the absence of direct sunlight (see Table 2 for technical specifications).

The entire system was integrated into a collar structure designed to meet IP65 standards for environmental protection, while maintaining lightweight and dynamic functionality suitable for use in extensive livestock systems (Banks Hughes, 2012; Rasmussen et al., 2020).

Table 2. Technical and Functional Specifications of the Wolf-Deterrent Collar.

Components	Technical and Functional Specifications
Collar Material	Technical plastic filaments (high thermal and mechanical resistance, low conductivity)
Manufacturing Technology	3D printing
Speakers	2 piezoelectric POFET, 30 Vp-p, range 2.5 Hz–60 kHz, 14.07 watts
Generator Module	Kemo M048N, adjustable 7–40 kHz, max intensity 110 dB
Operating Frequency	2.5 Hz–40 kHz
Power Supply Module	12 V solar panel (1.5 W) + 150 Ah rechargeable lithium-ion battery
Energy Autonomy	12 hours per day, up to 4 days without solar irradiation
Effective Range	Approximate useful radius of 50–100 meters, corresponding to 7,850–31,400 m^2 (variable based on topography, morphology, and climate)
Emission System	Modulated intervals of frequencies based on natural harmonic sounds

The acoustic emissions generated by the device consist of modulations of frequency intervals based on natural harmonic sounds also found in the bagpipe, a traditional musical instrument typical of the study area. The modulated frequency intervals, based on naturally produced harmonic sounds, cover a range from 105 Hz to 1200 Hz. The specific frequency intervals, listed in ascending order, are as follows: 105 Hz, 204 Hz, 219.766 Hz, 247.237 Hz, 274.707 Hz, 298 Hz, 302.178 Hz, 329.649 Hz, 386 Hz, 412.061 Hz, 439.473 Hz, 439.532 Hz, 471 Hz, 494.473 Hz, 549.415 Hz, 551 Hz, 604.357 Hz, 628 Hz, 659.298 Hz, 702 Hz, 773 Hz, 841 Hz, 847 Hz, 906 Hz, 969 Hz, 1030 Hz, 1088 Hz, 1145 Hz, and 1200 Hz (Di Giorgio, 2025). These frequency intervals, non-systematically modulated based on natural harmonics, are emitted by the wolf-deterrent collar.

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Figure 1. Wolf-deterrent Collar Prototype.

Under open-field conditions with minimal physical obstructions, the acoustic range of the deterrent collar was estimated to span between 50 and 100 meters, corresponding to a coverage area of approximately 7,850 to 31,400 m^2. This variability is influenced by local topographic and meteorological conditions, consistent with findings by Götz and Janik (2013) on terrestrial acoustic signal propagation [32]. The collar's design and cost-efficiency make it a viable and economically accessible solution for small-scale livestock farms operating in mountainous regions with elevated predation pressure. As such, it supports the development of sustainable coexistence strategies between extensive livestock production and wildlife conservation [50,51].

2.4. Retrospective and Progressive Data Comparison and Analysis

To evaluate the impact of wolf predation on goat farming, a retrospective analysis was conducted at Azienda Agricola Orlando Pietro between 2020 and 2024, with the objective of documenting the historical occurrence of wolf attacks in the area. Concurrently, the study assessed the effectiveness of the wolf-deterrent acoustic collar by comparing predation rates across three experimental groups (PC, PCG, and PCGC) during the field trial, thereby quantifying the device's ability to reduce predation events. In parallel, health and welfare indicators of the collared goats were continuously monitored to detect any potential adverse effects associated with the device's use [52].

Throughout the experimental period, each group was systematically monitored through direct visual inspections and ethological observations to document wolf–goat interactions. Observers recorded complete predation sequences, including stealthy approaches along vegetative cover, prolonged herd surveillance from a distance, and pursuit behaviors targeting isolated or vulnerable individuals. Both successful and unsuccessful predation attempts were meticulously documented, generating a comprehensive behavioral dataset.

The behavioral and predation data were then analyzed to assess the relative effectiveness of the acoustic collar compared with traditional livestock protection measures. This comparative assessment followed the methodological framework proposed by Boitani (2003) and commonly applied in human–predator conflict studies [1,22,53].

2.5. Camera Trapping

To confirm and monitor predator presence in the study area, two digital camera traps were installed approximately 100 meters from the livestock shelter (Figure 2), strategically positioned to maximize the likelihood of capturing high-resolution images and videos of wildlife.

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Figure 2. Georeferenced Topographic Map of the Orlando Pietro Study Site with Camera Traps and Livestock Infrastructure.

The camera traps (FP1 and FP2) used were Spypoint Flex-M Trail models, equipped with pre-activated SIM cards enabling real-time data transmission and continuous capture technology for constant monitoring [54]. These devices feature a detection radius of 27 meters and a trigger speed of 0.4 seconds, effectively documenting animal movement without disturbing natural behavior [55]. Camera traps operate in colour during the day and switch to black-and-white mode at night, using low-impact infrared illumination, and are securely mounted to trees with straps to ensure stability and security behavior [56].

3. Results

3.1. Predation Events in the Three Trail Groups

During the three-month experimental phase, substantial differences emerged between the treatment groups (Table 3):

Table 3. Monthly data on wolf attacks and prey recorded for the three experimental groups (PC, PCG, PCGC), and number of predator photos captured by two camera traps (FP1 and FP2) during the monitoring period (June–August 2024).

Group	Livestock Category	Month	Attacks	Prey	FP1(photos)	FP2 (photos)	Total Photos	Observations
PC	Goats	June	21	5	6	5	11	Constant nocturnal presence
PC	Goats	July	24	–	4	6	10	Filmed episode
PC	Goats	August	27	–	8	3	11	Constant nocturnal presence
PCG	Goats	June	11	1	5	4	9	Wolf passages
PCG	Goats	July	17	–	7	6	13	Increased activity at dusk

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Group	Livestock Category	Month	Attacks	Prey	FP1(photos)	FP2 (photos)	Total Photos	Observations
PCG	Goats	August	25	–	6	4	10	Observed pair movement
PCGC	Goats	June	0	0	7	4	11	Constant nocturnal presence
PCGC	Goats	July	1	–	6	5	11	Presence confirmed by video
PCGC	Goats	August	0	–	5	5	10	Observed pair movement

PC Group (Experienced Herder Only):

A total of 72 wolf attacks were recorded across the monitored groups, resulting in five confirmed goat fatalities, corresponding to a predation success rate of 7 %. Predation events predominantly occurred under meteorological conditions favorable to wolf activity, such as low visibility, moderate humidity, and light to moderate wind. Despite the presence of a herder, most lethal attacks were not successfully deterred. Field observations and carcass retrievals confirmed the impact of these events, with two fresh carcasses documented (Figure 4a) and three decomposed remains recovered (Figure 4b), further substantiating the extent of predation pressure [16,47].

Figure 3. Two Wolves Captured by Camera Trap FP2 While Attacking Livestock Within the Study Area on the Night of 13/06/2024. Supplementary materials: VideoS2 (https://youtu.be/PsHvPBckAJ0).

Figure 4. (**a**) Goat carcass from the PC group found on the ground immediately after predation; photograph taken on 13 June 2024, showing the initial condition of the body immediately after death. (**b**) Goat carcass in an advanced stage of decomposition, photographed on 30 July 2024, highlighting progressive tissue degradation and decomposition activity.

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PCG Group (Herder + Guardian Dogs):

In the group protected by both a herder and livestock guardian dogs (Maremma-Abruzzese and Sila breeds), a total of 53 wolf attacks were recorded—representing a 26.39% reduction in attack frequency compared to the PC group. Despite the high number of attempted predation events, only one goat was killed, resulting in a predation mortality rate of 2 %. These findings suggest that while guardian dogs significantly reduced the success rate of wolf attacks, they did not eliminate predation entirely [57].

PCGC Group (Herder + Guardian Dogs + Anti-Wolf Collar):

The group managed with a combined deterrent strategy—comprising an experienced herder, livestock guardian dogs, and an anti-wolf acoustic collar fitted to a sentinel goat (Figure 6)—recorded zero predation events during the trial period, despite consistent wolf presence confirmed by camera trap footage. Notably, in July 2024, a wolf was observed retreating from the herd in response to the combined deterrent effect of the collar and dogs. Supplementary materials: VideoS1(https://youtube.com/shorts/1L9QRykJnqo).

Figure 5. Adult female goat (approximately 3 years old) of the Aspromonte breed equipped with an anti-wolf collar at the study site of the Orlando Pietro livestock farm (Southern Calabria). This animal was selected for the trial as part of group PCGC during the monitoring period (June–August 2025) to evaluate the collar's effectiveness in deterring wolves under semi-extensive grazing conditions.

3.2. Retrospective Analysis of Predation Losses (2020–2024)

Historical records from Azienda Agricola Orlando Pietro between 2020 and 2024 revealed a substantial impact of wolf predation on livestock. Over this five-year period, a total of 148 goats were confirmed lost due to wolf attacks. The annual predation rate fluctuated, reaching a peak of 26.82% in 2024 (Table 4). When cumulative losses were compared to the 2024 herd size (150 animals), the resulting mortality rate was 98 %, underscoring the unsustainable nature of predation pressure in the absence of effective mitigation strategies [47].

Table 4. Annual numbers of goats in the stock, wolf predations, and predation percentage at Azienda Agricola Orlando Pietro (2020–2024).

Year	Goats on Farm	Goats Predated by Wolf	Percentage	Total Stock
2020	97	16	16 %	81
2021	101	11	10 %	98
2022	137	27	19 %	110
2023	236	39	16 %	197
2024	205	55	26 %	150

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3.3. Camera Trap Monitoring of Wolf Activity

The two camera traps recorded 54 images (FP1) and 42 images (FP2) of wolves, confirming persistent and regular predator activity across the monitored area (Table 4).

The even distribution of wolf detections between FP1 and FP2 suggests that wolves frequented all three grazing areas corresponding to the experimental groups (PC, PCG, and PCGC) (Table 4, Figure 3). Data presented in the table indicate that the groups equipped with acoustic collars, in combination with herder and livestock guardian dogs (PCGC), experienced significantly fewer predation events (0–1 attacks) compared to the PC and PCG groups, which recorded 11–25 attacks during the same period.

4. Discussion

4.1. Environmental Influences on Acoustic Deterrent Performance

The propagation of sound in atmospheric environments is governed by several physical parameters, including relative humidity, temperature, atmospheric pressure, and wind dynamics [58,59]. Among these, relative humidity plays a particularly critical role in modulating the absorption of high-frequency sound. Elevated humidity levels reduce acoustic attenuation—especially within the 2–8 kHz frequency range commonly employed in wildlife deterrent systems—thereby extending the effective transmission range of acoustic signals [32,60]. This effect is especially advantageous during nocturnal periods and in autumnal conditions, when ambient humidity tends to be higher.

Wind conditions also exert a significant influence on sound propagation. Favorable wind directions can enhance signal transmission by refracting sound waves along the wind path, whereas adverse or turbulent wind conditions may deflect sound trajectories or diminish sound pressure levels, thereby reducing the efficacy of deterrent systems [61,62].

Temperature gradients, particularly vertical thermal inversions—frequently occurring during evening and nighttime in mountainous regions—can further enhance lateral sound propagation through refraction, effectively expanding the acoustic coverage area [63]. These findings highlight the necessity of incorporating local topographic and meteorological variability into the design, calibration, and spatial deployment of acoustic deterrent devices. In complex terrains such as hilly or mountainous landscapes, where atmospheric dynamics are highly variable, site-specific acoustic performance assessments and adaptive calibration protocols are essential to ensure consistent operational effectiveness [32,64].

These environmental factors are particularly relevant for interpreting the results of this study and for assessing the potential application of the collars in different regions. Variations in humidity, wind, and temperature regimes may lead to differences in deterrent effectiveness, indicating that results obtained under Mediterranean conditions cannot be directly extrapolated to drier continental or alpine contexts. Therefore, site-specific trials and calibration are essential to validate the broader applicability of acoustic collars and to ensure consistent performance across diverse ecological and climatic scenarios.

4.2. Efficacy of Combined Protective Strategies

It is expected that a combination of traditional protection strategies and the benefit of the acoustic collar not only enhanced herd protection through predator deterrence but also, the wellbeing of the heard and improvement in milk yield via stress reduction.

In the control group (PC), which relied solely on human supervision, the highest rates of predation and livestock mortality were recorded. These findings align with previous research indicating that human presence alone is often insufficient to deter wolf attacks, particularly in topographically complex environments that facilitate predator ambush and escape [1,47].

In contrast, the second group (PCG), where herds were guarded by an experienced herder supported by livestock guardian dogs, experienced a 26.39% reduction in wolf attacks and a

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significant decrease in predation-related mortality to 1.49%. These results support existing literature on the effectiveness of guardian dogs in mitigating conflicts with large carnivores [57]. However, the persistence of sporadic predation events suggests that dogs alone may not provide complete protection, especially under sustained predation pressure.

The highest level of protection was observed in the third group (PCGC), which combined an experienced herder, guardian dogs, and a sentinel goat equipped with an anti-wolf acoustic collar. No predation events were recorded in this group despite confirmed wolf activity. The collar's acoustic deterrent appears to work synergistically with the defensive behavior of guardian dogs, enhancing overall herd protection. These findings are consistent with prior studies demonstrating the effectiveness of disruptive acoustic stimuli in deterring predator intrusions [30].

The device's effective coverage range (7,850–31,400 m^2) likely contributed to the absence of predation across all PCGC farms during the monitoring period (June–July 2025). While preliminary, these results suggest a strong deterrent effect of the acoustic collar in extensive grazing systems. Further longitudinal studies with larger sample sizes are needed to validate its long-term efficacy across diverse ecological and management contexts.

Importantly, the collar's modulated natural harmonic sounds appear to prevent predator habituation—a common limitation of repetitive acoustic stimuli [30,65]. These sound patterns are also likely to minimize stress in domestic livestock, as supported by research on ethologically compatible auditory stimuli [66–68].

Based on field observations, dogs show no reaction to noise, suggesting that it does not cause them fear

Camera trap data confirmed continuous wolf presence across all experimental groups, underscoring the high and persistent predation pressure. These findings highlight the urgent need for effective livestock protection strategies, as mortality rates can reach critical thresholds without adequate preventive measures [47].

Beyond reducing predation, the PCGC group according to the shepherds this group also showed improved productive performance, with an average daily milk yield of 30 L—15.38% higher than the 26 L recorded in the PC and PCG groups. This increase is plausibly linked to reduced stress levels due to the absence of predation, consistent with studies connecting lower environmental stress to enhanced milk production and animal welfare in small ruminants [69–72]. Also, no signs of acoustic-induced stress were observed in the livestock nor the dogs, such as escape attempts, altered feeding, or disrupted social interactions, behaviours that according to other studies indicate negative impact on animal welfare [73–76].

4.3. Perspectives and Work in Progress

As part of an ongoing pilot study aimed at testing innovative non-lethal tools for predator deterrence, three ovicaprine farms located within the Aspromonte National Park, in the province of Reggio Calabria (Southern Italy), were selected for the deployment of anti-wolf collars. Each farm—Romeo Carmelo (Bova), Romeo Giuseppe (Bova/Roghudi), and Stelitano Domenico (Bova Marina/Bova)—was equipped with three acoustic Anti-predation collars on June 3rd, 2025. All farms were in the transhumance period during the monitoring phase and manage approximately 150 goats and 150 sheep each.

From June 3rd to the present (late July 2025), no predation events or livestock losses attributable to wolves have been reported. While preliminary, these results indicate a potential deterrent effect of the device against wolf attacks in extensive grazing systems. Continued monitoring and an expanded sample size will be necessary to confirm these findings and evaluate long-term effectiveness under diverse ecological and management conditions.

Moreover, this deterrent supports the practice of transhumance, recognized by UNESCO (2019) as intangible cultural heritage, representing not only an ancient tradition but also a sustainable land management model [76]. Its value lies in combining biodiversity conservation with the maintenance

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of traditional knowledge and cultural landscapes, offering significant insights for developing pastoral practices compatible with environmental protection and coexistence with wildlife.

For future studies, an environmental impact assessment of the anti-wolf collar is proposed across all scientific fields to safeguard the environment and ensure sustainable development [77], and to validate this deterrent in contexts beyond the Mediterranean region.

5. Conclusions

Preliminary results from a field trial testing collars that emit high-frequency modulated natural harmonic sounds (ranging from 105 Hz to 1200 Hz) to deter wolves have shown promising outcomes. When used in combination with traditional protection methods—such as a herder and guardian dogs—the wolf-deterrent collar contributed to an almost complete elimination of livestock predation.

Given the significant threat that wolf predation poses to livestock, these findings warrant further investigation. Expanding the scope of research to include diverse habitats and different livestock species is essential to validate the collar's effectiveness under varied ecological and management conditions.

In conclusion, the integration of acoustic deterrent technology with traditional herding practices presents a compelling strategy for mitigating wolf-livestock conflicts. Scaling up these trials could pave the way for more sustainable and welfare-conscious livestock protection systems worldwide.

Supplementary Materials: The following supporting information can be downloaded at: Video S1: Wolf Repelled by Anti-Wolf Collar: Successful Deterrence in Action. https://youtube.com/shorts/1L9QRykJnqo ; Video S2: Wolf Predation on Livestock in Southern Calabria: Two Wolves Attack a Grazing Animal. https://youtu.be/PsHvPBckAJ0

Ethical Considerations: All animal-related activities were carried out in full compliance with relevant national regulations and the ethical standards of the institutions involved. During the monitoring phase, no procedures causing harm or distress to animals were performed. The pilot project adhered to all legal requirements concerning the protection of animal welfare and the proper management of livestock.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FP1	Camera Traps 1
FP2	Camera Traps 2
PC	Group Experienced Herder Only
PCG	Group Herder and Guardian Dogs
PCGC	Group Herder + Guardian Dogs + Anti-Wolf Collar

Appendix A

Appendix A.1

Table A1. Summary of key climatic parameters in the study area of Bova Marina (RC), southern Italy [42].

Parameter	Value / Range	Notes
Elevation	200 m a.s.l.	According to Italian Geographic Military Institute (2023)
Coordinates	37°57′01″ N, 15°56′37″ E	WGS84 system
Climate type	Mediterranean	Hot, dry summers; mild, wet winters
Annual mean temperature	9 °C to 31 °C	Peaks ~34 °C in summer, rarely <6 °C in winter
Annual precipitation	≈ 545 mm	Mostly concentrated in winter months
Warm season	mid-June to mid-September	Daily mean temperatures >28 °C
Cool season	late November to early April	Mean temperatures <18 °C
Peak solar radiation	July	Clear/partly cloudy skies ~96% of the time
Average wind speed	13–21 km/h	Seasonal variability can affect sound propagation
Relative humidity	Variable	Seasonally dependent; relevant for acoustic systems

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