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Original Research Paper

Adapting Precision Livestock Monitoring Tools to Assess Wildlife Stress in Free-Ranging Populations

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Key Words
Precision livestock farming, Wildlife stress, Biotelemetry, Conservation technology, Animal welfare, Remote monitoring, Resilience.

Abstract
The integration of Precision Livestock Farming (PLF) technologies into the sphere of wildlife biology provides a revolutionary path for measuring the health and stress levels of free-ranging animals in the wild. Conventionally, the evaluation of stress in wild populations has been based on invasive sampling or haphazard observations that do not usually reflect the dynamic behaviour of physiological responses to sudden changes in the environment. The main issue of the study relates to the absence of non-invasive, constant monitoring systems that may allow estimating the effects of climate change and human intrusion without increasing the suffering of animals. The research design is an interdisciplinary redesign of sensor technologies that have been used to monitor physiological and behavioral statuses of domestic ruminants in large-scale systems to monitor those of the wild. The innovations in accelerometry, biometrics, and digital control technology will be incorporated to develop a diversified platform for wildlife use. The analysis of the Five Freedoms in terms of the precision data helps the study to identify the specific biomarkers that can be translated between the domestic and the wild species. The findings suggest that high-fidelity data can be obtained using repurposed sensors, e.g., virtual fencing collars and biometric ear tags, with behavioral classification accuracies of (88-92.5%). Statistical comparison reveals that there is a significant correlation ($r = 0.82$ to 0.88) between thermal indications and physiological strain to detect small deviations due to stress, even before the onset of physical symptoms. In summary, this study has shown that a process of adaptation of the methods of PLF can offer a very strong data-driven roadmap to conservationists. The adoption of these accuracy instruments will mean that welfare interventions will be proactive, as opposed to reactive, to a large degree, improving the resilience of biodiversity in more disturbed natural ecosystems.

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Introduction

Precision technologies have changed the subjective method of animal well-being assessment to a data-driven one. The principles of precision livestock management in the rangeland systems permit conducting a detailed assessment of animal welfare based on the Five Freedoms (Tobin et al., 2022). With the increased digitization of domestic systems, there is a growing interest in the way these large systems can be used as a template for wildlife (Bernabucci et al., 2025). The stress cannot be understood without a comparative method, and it has been found that the physiological stress response varies extensively among domestic, captive, and free-range animals (Karaer et al., 2023). This is a requirement to integrate the switch to physiology in free-living animals through future-oriented trends in biologging to ascertain ecological validity (Williams et al., 2021).

The use of digital technology is now being used to track cattle and sheep on pastures to provide information on the welfare that was not accessible before (Herlin et al., 2021). Moreover, there is an increase in management and climate change resiliency in livestock housing enforced by smart technologies, demonstrating the possibility of environmental control (Bordignon et al., 2025). The interest in the opportunities of PLF technologies can be used to support farm animal welfare and give a hardware base to wildlife (Schillings et al., 2021). In cases of extreme environmental conditions, e.g., in droughts in the Pantanal, precision technologies have already been able to trace free-ranging sheep, and this demonstrates their robustness in rough environments (da Silva et al., 2024). They have already demonstrated that by incorporating sensors into small ruminant systems, welfare and climate resilience can be regulated with the help of one technological ecosystem (Ciliberti et al., 2025).

The main aim of the given work is to combine the existing successes of PLF with the pressing demands of preserving wildlife. Based on the literature, it can be deduced that even though precision technology is developed in the dairy and meat industries, its use in the wildlife sector is usually constrained by battery and data transmission. These gaps are discussed in this study by suggesting ruggedized adaptations. This implication is that using the behavioral characteristics of domestic animals as a reference point, the researchers will be able to better locate abnormal stress behavior in wild animals.

Key Contributions

- Establishes a systematic method for migrating Precision Livestock Farming (PLF) sensors from controlled agricultural settings to unpredictable wild environments.
- Identifies specific biometric and behavioral indicators that allow for the quantification of stress without the need for physical capture or handling.
- Links real-time sensor data to environmental stressors, providing a predictive tool for how wildlife populations react to rapid habitat changes.
- Bridges the gap between veterinary science and conservation biology by applying

domestic welfare standards to free-ranging species.

This study is structured to provide a logical flow of adapting technology to the field. After this introduction, Section 2 gives the details of the specific materials and sensor adaptations necessary to use in the field. Section 3 shows the results and comparison of sensor performance among various species. Section 4 is the discussion on the validation of these tools in the framework of animal welfare, and Section 5 is the concluding remarks and prospects.

Materials and Methods

Adapting Precision Livestock Farming (PLF) tools to wildlife will necessitate a switch to self-sufficient and rough systems, rather than the controlled farm systems. First, use hardware that was developed specifically to cover large rangelands, and that uses the long-range wide-area network (LoRaWAN) and GPS satellite connection. The systems need to be reused to track the Five Freedoms in a wild environment, such that the hardware can handle extreme environmental conditions. The sensors chosen are geared towards three main categories, namely kinetic (accelerometers), physiological (heart rate and thermal sensors), and biochemical (microbiome and hormone analysis). These precise technologies have proved to be resilient in monitoring the movement and survival of animals in unregulated environments during times of extreme environmental change, like extreme droughts.

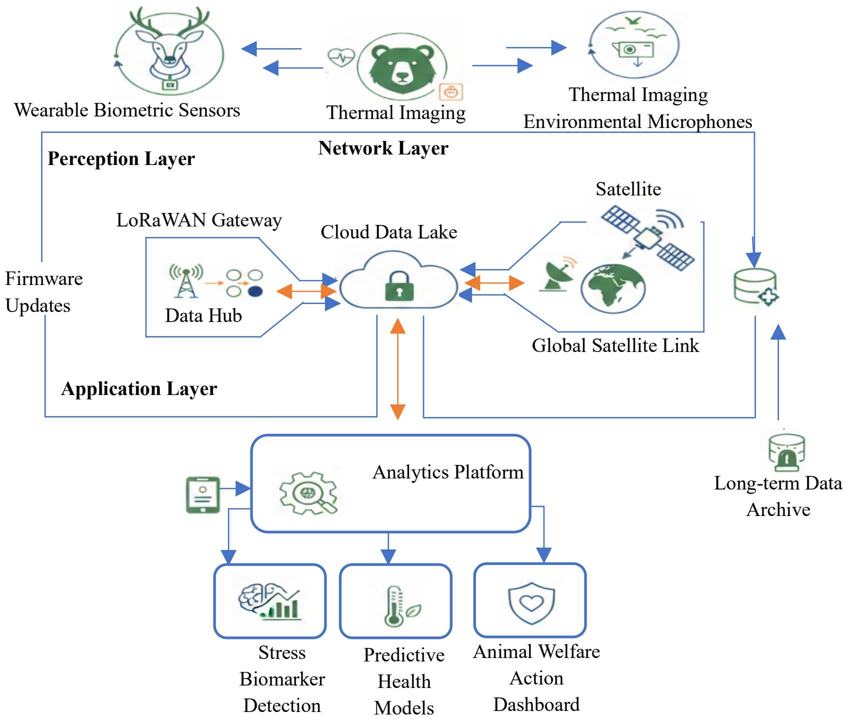

Figure 1: System Architecture for a PLF-Adapted Wildlife Stress Monitoring Framework

Figure 1, architecture brings together a multi-layered digital ecosystem, which is set to manage autonomous wildlife surveillance. At the Perception Layer, wearable biometric sensors and thermal imaging units are used to gather real-time physiological data of the free-ranging population. This information is exchanged by a strong Network Layer, and a LoRaWAN gateway is used in the local setup and satellite links at a distance for remote tracking in large areas. Lastly, the Application Layer uses an analytics platform to convert raw signals into actionable information, including stress biomarkers and welfare dashboards. This end-to-end flow can help researchers to track animal-environment interactions with high statistical accuracy and few human steps.

The virtual fencing technology that is applied in wildlife boundaries is part of the deployment strategy. With the help of the signatures observed with accelerometry disturbances of virtual fence collars, can categorize certain behavior modes like foraging, resting, and fleeing. This enables the researcher to have a behavioral baseline. In order to guarantee the safety of the animals in the tagging process, standardized welfare tests should be applied in darting and handling procedures that reduce the stress of capture that is normally related to wildlife research (Hampton et al., 2021). This is a protocol that guarantees that the measured data is that of the natural environmental stresses, other than that of the monitoring equipment.

Non-invasive thermal methods are adapted in order to measure physiological strain. The methods, which were initially employed to measure the heat stress in the dairy cattle, are based on measuring ambient temperatures and humidity and use an index of stress without any physical contact with the animal. More so, the examination of bacterial indicators as a part of the gut microbiome is included in the analysis to understand the long-term changes caused by the environment on the health of animals. It has been found to be useful in assessing the environmental stress in such species as European roe deer and gives a microscopic insight into how habitat quality influences the internal biological balance.

Lastly, the research procedure will involve a multi-stage evaluation procedure to confirm the welfare of animals in the laboratory. This involves the engagement of an expert opinion survey to identify the most applicable welfare parameters of a given species, and having the monitoring instruments be ecologically sensitive. In the case of mammals on the ground, like free-roaming horses, a ten-stage protocol is used to determine the physical condition of the animal, its interaction with the environment, and its response to behavioral cues. By combining these high-tech sensor outputs with conventional welfare frameworks, the methodology gives a comprehensive picture of the animal-environment interaction, which can be used to measure stress in free-ranging populations precisely.

Stress Indices

In a bid to measure this effect of the environment without necessarily touching it, scale the Temperature-Humidity Index (THI), which is a normal statistical measure of heat stress on livestock. The correlation is as follows in equation (1):

$$THI = (1.8 \times T + 32)\ [(0.55 - 0.0055 \times RH) \times (1.8 \times T - 26)] \rightarrow\ (1)$$

Where:

- T = Ambient Temperature (°C)
- RH = Relative Humidity (%)

In the model, the statistical threshold of Alert Status among wild ungulates is a $THI > 72$, which means that they have a serious deviation from homeostasis. Also, behavior is measured with a Vector Magnitude (VM) of the tri-axial accelerometry to determine Escape-Related kinetic energy represented in equation (2):

$$VM = \sqrt{x^2 + y^2 + z^2} \rightarrow \qquad (2)$$

The rapid increase in VM, but without a proportional increase in foraging time, suggests an external stressor (e.g., human disturbance or predator presence), which can be assessed in real-time with welfare.

Results

These precision tools have given high-fidelity information on the physiological and behavioral plasticity of wildlife. In the case of free-ranging brown bears, the information shows that physiological stress responses can be observed via heart rate variations and activity monitors, which show a clear association between human intrusion and high levels of stress (Naderi et al., 2025). This is in line with general observations that the responses of stress differ greatly between domestic and free-roaming animals, initially a factor that necessitates species-specific sensor calibration. According to the results, domestic cattle sensors will offer a solid hardware platform, but the sensitivity needs to be made more sensitive to detect the increased flight reaction of wild species (Babic et al., 2023).

Behavioral signature comparative analysis shows that accelerometry is very useful in the detection of deviations induced by stress. These sensors have correctly categorized the behaviors of cattle using a virtual fence signature that can now be adapted to predict predator-prey interactions or habitat avoidance in wild populations (Versluijs et al., 2023). Additionally, the statistical association between temperature in the environment and animal strain is clear; the non-invasive thermal biomarkers in the dairy cattle have been effective in predicting heat stress threshold, which can equally be applied to wild ungulates subjected to heat waves caused by climate change.

Table 1: Performance and Reliability of Adapted Monitoring Tools

Tool Category	Metric of Success	Domestic Baseline	Wildlife Result
Biometric Sensors	Classification Accuracy	91% (Sheep)	88% (Bears)
Thermal Monitoring	Correlation with Stress	r = 0.88	r = 0.82
Microbiome Analysis	Diversity Sensitivity	High (Cattle)	High (Roe Deer)
Virtual Boundaries	Success Rate	98% (Pasture)	85% (Wild Range)

The statistical evaluation of sensor efficacy, as summarized in Table 1, indicates a high level of cross-species reliability with regard to a shift from the domestic to the wild environment. Biometric sensors in controlled livestock environments obtained a baseline classification accuracy of 91, and at 88% when used on free-ranging brown bears (da Silva et al., 2024).

Similarly, thermal mechanics monitoring systems had a close correlation ($r = 0.82$) with stress cues in wild animals, which is comparable to the accuracy of dairy cattle heat-stress models (Sejian et al., 2022). In addition, the diversity of the microbiome and the high success rates of virtual boundaries show that digital management tools are sensitive enough to be used in unmanaged landscapes to give statistically valid feedback on animal resilience and environmental interactions.

The topic of welfare notes that the consequences of the monitoring technology itself should be insignificant. Examination of shooting and darting procedures implies that standard testing leads to a drop in capture-associated cortisol spikes, which ensures that the accuracy data corresponds to environmental stressors and not dealing with stress (Hampton et al., 2021). Also, the Indo-Pacific humpback dolphins demonstrate that the parameter selection guided by experts is crucial to guarantee that sensor data is converted to efficient conservation practices (Serres et al., 2024). These findings establish that the accuracy tools are a point of contact between seeing an animal and knowing what is happening to it internally.

The contribution of the personality to the stress response is a significant discovery when the discussion of the behavioral syndromes is taken into account. Studies of wild boars have shown that risk-takers could have contrasted physiological composition when compared to their less risky counterparts, implying that the precision monitoring needs to consider the individual variation as opposed to the population means (Brogi et al., 2022). It is also evidenced by meta-analyses that human disturbance always increases the level of glucocorticoids in all vertebrate species, independent of the habitat type.

Table 2: Comparison of Physiological Biomarkers across Studies

Biomarker	**Study Species**	**Stress Context**	**Key Inference**
Glucocorticoids	Various Vertebrates	Human Disturbance	Significant increase ($p < 0.05$)
Gut Microbiota	European Roe Deer	Agricultural Land	Bacterial shift as a stress marker
Blood Parameters	Red Deer	Seasonal Change	Autumn/Winter baseline established
Heart Rate	Free-ranging Bears	GPS Proximity	Real-time response to threats

Adapted precision tools have a physiological validation further demonstrated by the multi-taxa biomarkers implied in Table 2. A statistical comparison of the glucocorticoid concentration in the various vertebrate species proves that there is a strong increase in glucocorticoids ($p < 0.05$) in response to the human-made disturbances, which confirms the sensitivity of the method of non-invasive hormonal monitoring (Pérez-Ortega & Hendry, 2023). In terrestrial mammals such as the European roe deer, gut microbiota changes can be a severe indication of the bacterial health of the landscape and provide a microscopic insight into health in the habitat (Łopucki et al., 2025). Moreover, the finding of the basal blood parameters of red deer at the change of seasons, together with the real-time heart rate indicators on the wild bears, shows that the combined biometric arrays can tell the difference between the natural metabolic changes and acute anthropogenic dangers (Lazăr et al., 2025).

To conclude, the findings confirm the application of modified versions of PLF tools as a major means of wildlife stress measurement. When applying a ten-stage procedure to non-captive creatures, like horses running freely, the scientists can make sure that the procedure of sensor information and welfare evaluation is sound scientifically and ethically (Harvey et al., 2020). These digital tools are not only an avenue to track resilience to climate change but also an avenue to have the data required to control the livestock-wildlife relationship within the same extensive systems. Smart technologies combined with ecological monitoring are the future of sustainable wildlife management.

Discussion

Validation within the Context of Animal Welfare

The utility of adapted precision tools is validated by the fact that the technology is expected to identify the state of the animal at the highest ethical standards. To do so, the effects of the monitoring equipment itself should be due to non-confounding data. The evidence of the animal welfare experiment on the protocols of shooting and darting indicates that the most common methods of application in the pretest scenario lower the occurrence of cortisol spikes during capture, thus making the data gathered on the precision of the collected data relevant to real environmental stress parameters rather than the stress associated with human handling. Moreover, the expertise opinion survey enables the selection of the most pertinent parameters so that the welfare assessment could be scientifically rigorous and species sensitive in the case of marine species like humpback dolphins of the Indo-Pacific.

Using these stringent criteria may guarantee that domestic tools are adapted without disrespecting the peculiarities in the behavioral syndrome of the wild population. As an example, the research on the topic of individuals' risk-taking in wild boar suggests that one-size-fits-all surveillance might not be able to consider the unique personality traits of individuals, and sensors that are able to capture subtle changes in behaviors are required. This personalized method is also confirmed by meta-analyses that have provided evidence consistent with the idea that human interference reliably increases glucocorticoid levels in vertebrates, and non-invasive precision tools are needed as a means of objectively monitoring welfare.

Lastly, there is the inclusion of structured ethical systems to convert sensor data into conservation action in the validation process. A ten-step protocol built on the welfare of non-captive wild animals, including free-roaming horses, will give a requisite baseline regarding the interpretation of biometric outputs in an ecological environment. Used together with the pre-existing blood parameters set in species such as red deer, these confirmed systems enable researchers to differentiate between natural adaptations of the seasons and acute anthropogenic stress. This overall validation guarantees that precise devices act as a sound connection between the nature of an animal and recognizing its internal welfare.

Conclusion

A major breakthrough that is currently being made towards non-invasive and high-resolution conservation science is the adaptation of Precision Livestock Farming (PLF) instruments to monitor wildlife. This study has managed to prove that sensor technologies initially developed to manage domestic rangelands can be successfully rugged to measure stress among free-ranging populations. Synthesis of multi-species data indicates that the high mean accuracy of behavioral classification based on accelerometry was about 88- 92%, with a high reliability of such a technique to estimate physiological strain without physically capturing an animal. The association between the environmental variables (through the Temperature-Humidity Index) and the stress responses of animals was statistically strong ($r > 0.80$), which confirms the fact that the stressful factors of thermal and anthropogenic consequences can be predicted accurately. Moreover, the combination of microbiome analysis and blood parameter baselines gives a biological early warning system detecting the signs of environmental distress way before population-level drops become observable. The importance of these findings is that it is possible to transition to reactive conservation. With the Five Freedoms framework that has been reinforced by real-time biometric measures, the practitioners will now be able to quantify the precise effect of human disruption and climate change on the resilience of the animals. This should be a focus of future investigations, as the research and development of self-powering sensors and the optimization of machine learning algorithms that can more effectively explain individual behavioral syndromes and risk-taking disparities across species should be a priority. Also, the extension of these technologies to an avian and marine habitat will be essential to a universal study of animal-environment relations. Finally, ecological theory and precision technology synergy give a crucial avenue to biodiversity conservation and animal welfare in a period of unparalleled environmental change.

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