Journal of Animal Environment
(E-ISSN 2717-1396, ISSN 2717-1388)
Journal homepage: https://aejournals.org/

Original Research Paper

Behaviour Sense: A Machine Learning Framework for Predicting Wildlife Behavioural Adaptations Under Ecological Stress

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Key Words

Behavioural adaptation, Ecological stress, Wildlife behaviour, Predictive modeling, Behavioural ecology, Conservation biology, Stress assessment.

Abstract

Wildlife populations all around the world have become increasingly prone to ecological stressors such as habitat deterioration, limited resources, temperature extremities, and increased predation. Behavioural adaptation is one of the quickest ways in which animals respond to such conditions. However, unlike physiological and demographic adaptations, behavioural changes are more likely to precede the development of any other adaptive responses and be relatively easy to reverse. In this paper, Behaviour Sense is introduced– a predictive model based on behavioural and ecological data that is capable of predicting how free-living and captive wildlife populations will adapt their activity patterns, foraging behaviour, movement patterns, and social structure in case of exposure to ecological stress. Instead of using solely retrospective observation data, this model relies on longitudinal behavioural data, physiological indicators of stress and environmental factors in order to produce early indicators of stress-related behavioural changes at the level of a whole species. Based on the literature in behavioural ecology and conservation biology, conceptual validation shows that such predictive approaches can significantly reduce the time needed for identification of ecological stress by wildlife populations.

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Received: 25th May, 2026; Revised: 6th June, 2026; Accepted: 8th June, 2026; Available Online: 07th August, 2026
(DOI): 10.70102/AEJ.2026.18.3s.91

Introduction

Behavioural flexibility is among the main ways through which animals respond to changes in their surroundings. Way before there are any measurable changes in body state, reproductive performance, and population number, changes tend to be evident in how individual animals distribute their time in foraging, vigilance, resting, and interacting socially (Tuia et al., 2022). The importance of such early behaviour changes is due to the fact that such are the way in which animals react to stressful situations in their habitat and way before any measurable effects can be documented through monitoring. The fact that such observations have always been laborious makes it difficult to conduct such studies on large groups and across different species.

Technological improvements in bio-logging, remote sensing, and automated behaviour recognition have increased the amount of behavioural data at the disposal of wildlife ecologists (Tuia et al., 2022; Jeantet et al., 2026). Devices such as wearable accelerometers, camera traps, and posture analysis devices can be used by ecologists to monitor fine movement and posture continuously in places where it was not possible for humans to observe before (Rast et al., 2020; Agarwal et al., 2026). The increase in the availability of behavioural data has presented ecologists with the opportunity to go beyond descriptive behavioural ecology into predictive behavioural ecology, whereby patterns detected through many individuals and populations are used to predict how an animal will behave in poor ecological conditions.

This paper proposes Behaviour Sense, which is a predictive model that was developed explicitly for animal science and wildlife biology. The model was developed to serve as an additional tool for the estimation of stress levels among animals, alongside traditional field and laboratory techniques such as glucocorticoid measurement, body condition score assessment, and direct observation of behaviours using ethogram.

Key Contributions

- Outlines a machine learning framework to predict behavioural adaptation in animals in times of ecological stress.
- Includes behavioural time series, ecological stress factors, and predictive modeling for early stress identification.
- Enables proactive conservation, wildlife management, and animal welfare via species-specific behavioural prediction.

This paper is structured as follows. Section 2 is on ecological stress and behavioural adaptation in animals. Section 3 covers the Behaviour Sense approach. The applicability of Behaviour Sense is covered in Section 4. Validation concerns are discussed in Section 5 and conclusions are provided in Section 6.

Ecological Stress and Behavioural Adaptation in Wildlife

Ecological stress occurs when environmental conditions become different from what an organism's physiology and behaviour are adapted to. Ecological stressors can be low availability of food, habitat loss or alteration, exposure to extreme temperatures, high levels of

human activity, as well as changes in the density of predators or competitors. Organisms react to ecological stress in a series of responses, starting with behavioural reactions, followed by physiological responses like glucocorticoids secretion and eventually demographic ones, if the stressor continues (Padmanaban et al., 2025).

The known behavioural reactions to ecological stressors are numerous and recurrent across taxa. Elevated levels of vigilance behaviour and decreased foraging time have been observed in populations experiencing higher predation pressure and human disturbances (Padmanaban et al., 2025). The thermal stressor usually leads to modification of the activity pattern to avoid the peak temperature period and utilize more shade or refuge sites. Lack of resources may result in the increase of the home range, modifications in the efficiency of movement, and alterations of social aggregation due to the changes in the effort of searching and tolerance of conspecifics in conditions of competition. Repetitive stereotypical movements that are different from the natural behavioural repertoire of the species are a usual reaction of an animal to stress in captivity or management and widely applied as welfare parameters (Zuerl et al., 2024).

One consistent observation made throughout these works is that behavioural reactions to stress are gradual and accumulative in nature, as opposed to being an either/or scenario. Stressors that are mild or temporary elicit small changes in activity levels that can only be recognized through close and continuous monitoring of the subjects, whereas stressors that are constant lead to more noticeable changes in the behaviour of the subjects (Agarwal et al., 2026; Padmanaban et al., 2025). The gradual nature of stress is crucial in the development of Behaviour Sense.

The Behaviour Sense Framework

The Behaviour Sense architecture is based on three interconnected modules; the behavioural data module, the ecological stressors module and the behavioural risk prediction module. All these modules are based on existing data streams in animal sciences and can therefore be populated with methods of data collection that are already known to wildlife biologists and animal behaviourists.

Behavioural Data Layer

The behavioural data layer brings together continuous behavioural records of a community or population under observation. Sources that may be used in this layer include acceleration-GPS-derived activity budget, activity and space usage records using camera traps, and ethogram records obtained via direct observations and video (Rast et al., 2020; Agarwal et al., 2026; Otsuka et al., 2024). Variables of interest include foraging time, resting time, vigilance behaviour, locomotive behaviour, and social behaviour, as well as movement parameters like range usage and diel movement pattern. In case stress-related behaviour can be detected, this layer captures them since such behaviours are good indicators of deviation from normal behaviours (Zuerl et al., 2024; Padmanaban et al., 2025).

Ecological Stressor Layer

The ecological stressor layer matches behaviour with corresponding environmental and

anthropogenic stresses such as anomalous temperatures and rainfall, forage/prey indexes, habitat disruption/fragmentation indexes, and indexes of human or predatory pressure. With this, the ecological background for the behavioural changes becomes clear, making it possible to connect any particular change in behaviour with a certain kind of stressor instead of treating it as an outlier.

Predictive Behavioural-Risk Layer

In the predictive layer, the two layers mentioned above (the behavioural layer and the stressor layer) are combined in order to predict the probability and expected shape of behavioural adaptations in response to a certain stress scenario. This layer is trained using past behavioural adaptations in response to the stressors that are known. In other words, the predictive layer is trained by identifying which combinations of the environmental changes lead to certain behaviours, for example, reduction in foraging time, change in activity patterns or heightened vigilance. Due to the fact that behavioural adaptations to stress are graded, the predictive layer is aimed at predicting continuous behavioural risk, and not presence or absence of it (Zuerl et al., 2024).

Species and population specific calibration is an important aspect in the design of Behaviour Sense. Due to the fact that different species and populations have varied baseline activity budgets and stress thresholds, the system is expected to be calibrated independently for each monitored population based on the history of behaviour and environment associated with such population, following the example set forth by recent behavioural classification systems which consider changes in performance across ecologies (Agarwal et al., 2026).

Application Contexts

This framework is useful in various animal science applications. In free-ranging wildlife studies, the Behaviour Sense system can be used to assess any population already fitted with bio-logging devices and provide early warning signs of behavioural stress related to drought, habitat destruction, or human encroachment, to allow for appropriate management interventions, such as habitat protection and additional resource allocation (Tuia et al., 2022; Jeantet et al., 2026). In fisheries and aquatic studies, similar behavioural metrics, including changes in swim patterns and seeking refuge, have been used to quantify behaviours associated with predator stress and environmental variability, and can be adapted into the same model (Padmanaban et al., 2025). Within the zoo and aquarium industries, as well as other managed care facilities, the framework can facilitate the early detection of any increase in stereotypic behaviours before they become ingrained, and serve as another component of automated welfare monitoring systems (Otsuka et al., 2024; Zuerl et al., 2024). In all three cases, the basic principle at work is identical: Ecological stress triggers a distinct behavioural response, which precedes any other biological changes and affords an opportunity for intervention.

Validation Considerations and Limitations

Any framework of prediction for behaviour needs strong validation through behavioural data that have been acquired in baseline as well as known stress scenarios, preferably in terms of stress indicators of physiology, like glucocorticoid metabolite concentration levels. The studies that use behaviour classification have highlighted that predictive power may vary greatly while transferring a model to an individual or a population or an environment that differs from the one it was trained on (Agarwal et al., 2026; Otsuka et al., 2024). It is an additional drawback that behavioural adaptation is not necessarily a clear indicator of danger. Some behaviours may change and become more varied as a result of an adaptive response to the environment that enables survival rather than the indication of future decline. Such behavioural changes need to be interpreted in light of ecology of the species (Padmanaban et al., 2025).

Conclusion

Behavioural adaptation is one of the earliest, and most sensitive, measures of ecological stress in wildlife, manifesting itself long before any physiological or demographic consequences are seen. The Behaviour Sense protocol proposed in this paper presents a systematic means of combining behavioural monitoring data and ecological stressors to forecast behavioural adaptation in free-ranging, aquatic, and captive wildlife. In developing a protocol that makes the connection explicit between certain ecological stressors and the behaviour they are likely to produce; the possibility exists of reducing the lag between environmental stress occurring and the scientific community's ability to recognize and respond to it. Further work needs to be done in validating the predictions of this framework through field tests involving a wider variety of taxa and stressors, as well as incorporating physiological measures of stress into the analysis.

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