17(4) 419-433, Winter 2025

Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Journal homepage: http://www.aejournal.ir

Original Research Paper

Mapping Behavioural Landscapes of Fear in Agroecosystems and Impact on Agricultural Sustainability

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Key Words

Agroecosystems, Behavioral ecology, Ecosystem services, Human activity, Landscape of fear, Multivariate analysis, Sustainability.

Abstract

Agroecosystems are multifaceted socio-ecological systems in the interaction of wildlife, humans, and agricultural activities, which determine spatial and temporal risk perception landscapes, called landscapes of fear. This paper set out to map behavioural terrains of fear in agroecosystems and evaluate their relevance to the sustainability of agriculture. In particular, it assessed spatial distributions of natural and human-induced risk factors, measured animal behavior responses, and interconnected fear-mediated behavior with the outcomes of ecosystem services. The experiment had been performed in mixed-use landscapes that included intensive croplands, pastures, hedges, and remnant vegetation. Camera traps, direct observations, and GPS telemetry were used to collect behavioral observations of herbivores, omnivores, and insectivorous species. Risk factors such as predator distribution, the anisotropy of the environment, the level of human activity, the concentration of infrastructure, as well as the exposure to pesticides, were standardized and spatially interpolated to create continuum risk surfaces. The Landscape of Fear Index (LoFI) was calculated by integrating behavioral responses, and relationships with sustainability indicators (crop damage, pest suppression, pollination, and yield variability) were analyzed using generalized linear mixed models (GLMMs), spatial regression, and multivariate analyses (PCA/RDA). Findings showed that there was a significant level of spatial heterogeneity of perceived risk. The highest LoFI was observed in intensive croplands (0.78 ± 0.14), and the lowest in remnant vegetation (0.22 ± 0.06), indicating the perceived threat in the human dominion area. Behavioral response was related to risk gradients, with a lower frequency of visitation, foraging time, and higher vigilance and avoidance in high-risk zones. GLMM analyses indicated a negative relationship between crop damage and LoFI ($\beta = -0.63$, $p < 0.001$), pest suppressive activity ($\beta = 0.41$, $p < 0.001$), and pollination activity ($\beta = 0.27$, $p = 0.001$) was maximal at intermediate levels of fear. Multivariate analyses confirmed anthropogenic pressures, and LoFI explained substantial variance in behavioral and ecosystem service metrics.

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Received: 10 September 2025; Reviewed: 17 October 2025; Revised: 26 November 2025; Accepted: 29 December 2025
(DOI): 10.70102/AEJ.2025.17.4.33

Introduction

Agroecosystems are socio-ecological processes in which agricultural production, in one form or another, co-exists with wildlife, livestock, and human activity. In these systems, animals constantly evaluate spatial and temporal changes in the threat of predation, anthropogenic disturbance, and the abundance of resources, which is what is known as a landscape of fear (Amato & Petit, 2023). The landscape of fear framework is traditionally used in studying the natural ecosystems, with perceived risk being the main driver of the animal movement, habitat utilization, and foraging behavior, rather than direct mortality. Anthropogenic effects are also increasing the causes of fear response in the agroecosystems, which include farm machines, fences, crop harvesting, the use of pesticides, and human presence. Such behavioral changes have the potential to change grazing behavior, crop-raiding interactions, pest control, and nutrient recycling, and have indirect but significant effects on agricultural output and sustainability. The nature of fear-based behavioral fields in tamed agricultural systems is hence paramount to achieving a balance between food production and ecological stability (Ouerghemmi et al., 2024; Capella et al., 2023).

The main aim of the research is to map behavioural regions of fear in agroecosystems and assess their consequences on the sustainability of agriculture. In particular, the research will define spatial patterns of perceived risk in agricultural landscapes, discuss the ways in which these patterns impact animal movement and resource use, as well as measure the cascading effects of the fear-mediated behavior on the stability of crop yields, ecosystem services, and interactions between humans and wild animals.

Despite the recent popularity of the fear ecology concept, most of the existing literature is rooted in the observation of the sheltered or the natural ecosystems, and little experience is obtained of the strongly controlled agricultural landscapes. Current literature is more inclined to the direct damage of crops or control of wildlife and general disregard of the sub-lethal behavioral mechanisms through which fear may affect ecological processes in farmlands (Narzari et al., 2025). Moreover, there are no linkage frameworks to combine behavioral ecology, spatial modeling, and agricultural sustainability indices. Evidence-based and non-lethal management practices cannot be implemented due to the deficit of fine-scale spatial mapping of the fear response in agroecosystems (Muxitdinov, 2023).

The study hypothesizes that the agroecosystems have heterogeneous landscapes of fear that are shaped by the natural and anthropogenic risk factors, resulting in predictable spatial avoidance and changes in activity patterns in the animals. It is also postulated that behavioral changes caused by fear have a far-reaching effect on ecosystem processes like pest control, crop foraging stress, and nutrient redistribution of soil, and this leads to agricultural sustainability outcomes.

This study contributes a novel, integrative approach to understanding agroecosystems by explicitly mapping behavioural landscapes of fear and linking them to sustainability indicators. The study, to fill the gap between behavioral ecology and agricultural science, offers spatially explicit information on the role of non-lethal fear effects in mediating the relationship between humans and wildlife and agricultural output. The results provide a basis to develop adaptive land-use activities and wildlife management plans to increase productivity and support ecological alacrity and sustainable agriculture.

The article has been organized in a way that gives an in-depth analysis of the fear-mediated behavioral landscapes in the agroecosystems and their ecological consequences. The introduction starts with the concept of the landscape of fear, objective, hypothesis, and research gaps. The Literature Survey synthesizes prior studies on fear ecology, agroecosystem behavior, and ecosystem service interactions. The materials and methods describe the study area, Behavioral observations, specimen species, risk factors mapping, and statistical and spatial analysis (GLMM, GAM, PCA/RDA). Results present spatial risk distributions, behavioral responses, LoFI patterns, and links to sustainability indicators. The ecological and management implications and limitations, as well as future directions, are discussed, and a conclusion is presented that summarizes the main findings and conclusions on the sustainable management of agroecosystems.

Literature survey

The idea of the landscape of fear has come to be broadened to include more perceptions of risk arising from both biotic and anthropogenic factors than the classical theory of predator-prey. The concept of redefining the landscape of fear as a safety eco-field, presented by (Farina & James, 2023), focuses on cognitive and semiotic signals that control the choice of animals. This view is especially applicable in agroecosystems where animals react to the presence of humans, agricultural infrastructure, management practices, and the natural predators.

Empirical studies are increasingly demonstrating that fear-mediated behaviors play a very important role in wildlife-crop interactions. The complex interactions between food availability, perceived risk, and management interventions (Widén et al., 2023) also show that indirect effects of fear cause crop damage by ungulates, which can be used to articulate the significance of indirect fear effects. Conversely, it is demonstrated (Rigoudy et al., 2024) that crop phenology dynamically redefines food-safety tradeoffs of roe deer, generating a temporally changing landscape of fear on agricultural mosaics. These studies have highlighted the necessity to ensure a shift in method in favor of spatially explicit behavioral mapping, as opposed to the stagnant damage measurements.

Effects of fear also affect across trophic levels, which affect ecosystem services in agroecosystems. As (Roseo et al., 2024) disclose, the abundance of barn swallows in dairy farms disrupts the activity of pest flies by establishing a local fear of them, which increases the biological control of pests. This may be consistent with the frameworks of ecosystem (dis)service cascades suggested by (Blanco et al., 2022), which attribute behavioral responses to more extensive sustainability results. Human perceptions also mediate these dynamics (Meli et al., 2024) and demonstrate that perceived ecosystem disservices may compromise acceptance of species of benefit, including bats.

Fear-driven behaviors are extremely subject to landscape configuration and land-use intensity. Research in a wide range of agroecosystems shows that woody cover, pasture structure, and matrix composition define the occupancy and space use of mammals (Nanni et al., 2023; Aikawa & Saito, 2023). Nevertheless, cultivated areas still contribute little to the biodiversity and behavioral data, leaving huge knowledge gaps (Remelgado et al., 2025). This weakness is strengthened by the fact that the conceptualization of landscape is not always consistent in studies of sustainable agriculture (Pereponova et al., 2023).

There are anthropogenic stressors, including the use of pesticides, which make behavioral landscapes even more complex. Exposure hazards to mammals in farming are determined, whereas interactive impacts of habitat structure and chemical contributions on pollination services are demonstrated (Gebhardt et al., 2025). These results point to the fact that agricultural inputs have a direct and indirect impact on behavior via fear-mediated avoidance.

Regarding the agroecosystems, they can be viewed as complex adaptive systems, in which behavioral responses, management practices, and ecological processes interact nonlinearly (Schiere & Gregorini, 2023; Adams et al., 2025; Jayaraman & Kumar, 2024). Agroecological systems and collective action were discovered to enhance resilience and reduce reliance on harmful inputs (Veisi et al., 2025; Ahmad & Köpke, 2024; Parmantier et al., 2026). Nevertheless, in spite of these accomplishments, there has been a lack of integrative frameworks between behavioral landscapes of fear and agricultural sustainability, and hence the need to implement spatially explicit and interdisciplinary strategies.

Materials and methods

Study Area and Agroecosystem Characterization

The experiment was done in a mixed-use agroecosystem of croplands, pasture patches, hedgerows, and remnant natural vegetation. The stratification of the landscape was in accordance with the type of land-use, the phenology of crops, and the level of human activity. Spatial data layers (land cover, field boundaries, water sources, road networks, and pesticide application zones) were created by means of high-resolution satellite images and ground-truth surveys. Climatic variables and seasonal cropping cycles were recorded to capture temporal variability in risk perception.

Figure 1 illustrates the integration of land-use patterns, natural and anthropogenic risk factors, and wildlife behavioural responses to generate spatial landscapes of fear. These fear gradients are linked to key agricultural sustainability indicators, including crop damage, pest suppression, pollination activity, and yield variability, within a unified spatial–statistical analytical framework.

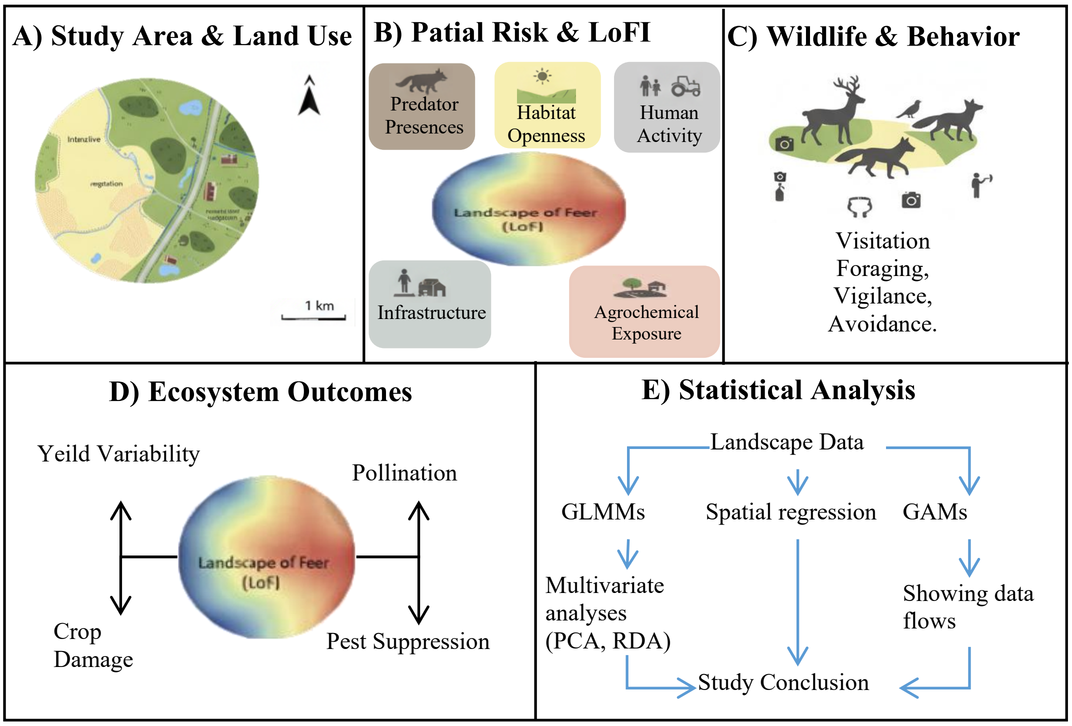

Figure 1: Conceptual–Spatial Framework Linking Fear Landscapes to Agroecosystem Sustainability

Focal Species and Behavioural Data Collection

Representative wildlife functional groups on the agroecosystem dynamics were observed in behaviour, such as medium-sized herbivores, omnivores, and insectivorous species. The movement and activity patterns of animals were observed with the help of a combination of camera traps, live observations, and GPS telemetry when possible. The behavioural measures, including visitation frequency, foraging time, vigilance behaviour, and avoidance behaviour, were measured in various land-use patches and management regimes.

Risk Factor Identification and Spatial Risk Mapping

Perceived risk was formulated as a combination of natural and man-made factors. The natural risk was the availability of predators, the availability of the natural habitat, and the vegetation structure, and the anthropogenic risk entailed the intensity of human activity, the presence of farm infrastructure, machinery movement, and agrochemical application areas. All risk factors were standardized and spatially interpolated by GIS-based methods to produce continuous risk surfaces all over the study area.

Linking Fear Landscapes to Agricultural Sustainability Indicators

Indicators such as intensity of crop damage, pest suppression rates, pollination activity, and spatial variability of yield at the agricultural field were used to determine the sustainability of agriculture. These indicators were spatially overlaid with LoFI maps to examine correlations between fear intensity and ecosystem service outcomes. Generalized linear models and spatial regression analyses were used to test relationships between fear landscapes and sustainability metrics while accounting for land-use type and seasonal variation.

Statistical and Spatial Analysis

All analyses were conducted within an integrated spatial–statistical framework using R (v4.x) for statistical modeling. Behavioural, environmental, and agricultural datasets were standardized to a common spatial and temporal resolution prior to analysis.

Animal behavioural responses (visitation frequency, foraging duration, vigilance) were analyzed using generalized linear mixed models (GLMMs) implemented in the *lme4* package. The Landscape of Fear Index (LoFI), land-use type, and season were treated as fixed effects, while site and sampling period were included as random effects. Appropriate error distributions were selected based on response variable characteristics.

Spatial relationships between fear intensity and agricultural sustainability indicators, crop damage, pest suppression, pollination activity, and yield variability, were evaluated using spatial regression models (spatial lag and spatial error) via the *spdep* package. Moran's I and LISA statistics were used to measure spatial autocorrelation.

Generalized additive models (GAMs) were fitted with mgcv to fit nonlinear responses on fear gradients. PCA and RDA (vegan package) were used to examine multivariate linkages between risk factors, behavioral metrics, and sustainability outcomes. The AIC, deviance explained, and cross-validation were used as performance measures of models, and sensitivity analysis was used to test the strength of the weighting schemes used by LoFI.

Results

Spatial Distribution of Risk Factors Across the Agroecosystem

The results of the spatial analysis showed that the perceived risk was highly heterogeneous in the agroecosystem. The anthropogenic risk factors, especially the proximity to roads, agricultural infrastructures, and the zones of pesticide applications, were concentrated in intensively cultivated croplands, whereas the natural risk factors, like predator population and openness of habitats, were increased in the hedges and patches of remnant vegetation. The changing risk distribution due to seasonal change in crop phenology was highest during the anthropogenic risk sowing and harvest periods.

Table 1 summarizes variation in ecological and anthropogenic indicators across different land-use types. High human modification is reflected in intensive cropland with the least predator abundance and the greatest openness of habitats, intense human activities, dense infrastructure, and pesticide exposure. Most variables are intermediate in pasture systems, which implies moderate disturbance. Hedges and remaining vegetation, in turn, maintain a high predator abundance and reduce habitat openness, human activity, levels of infrastructure density, and exposure to pesticides, demonstrating them as relatively undisrupted habitats and key biodiversity refuges in modified landscapes.

Table 1: Summary statistics of standardized risk factors across land-use types

Land-use Type	Predator Presence (index)	Habitat Openness (index)	Human Activity Intensity (index)	Infrastructure Density (km/km²)	Pesticide Exposure (index)
Intensive Cropland	0.21 ± 0.08	0.87 ± 0.06	0.91 ± 0.05	3.6 ± 0.7	0.84 ± 0.09
Pasture	0.38 ± 0.12	0.63 ± 0.10	0.54 ± 0.11	1.9 ± 0.5	0.32 ± 0.07
Hedgerows	0.62 ± 0.14	0.31 ± 0.09	0.29 ± 0.08	0.8 ± 0.3	0.14 ± 0.05
Remnant Vegetation	0.71 ± 0.13	0.24 ± 0.07	0.18 ± 0.06	0.4 ± 0.2	0.08 ± 0.03

Behavioural Responses Across Land-Use Types

There was a high difference in behavioural metrics across land-use categories. Visitation frequency and foraging duration were highest in low-risk patches such as pasture margins and hedgerows, while vigilance rates and avoidance behavior increased sharply in high-intensity croplands. Insectivorous species were less active in the area of pesticide treatment, and herbivores were highly time-shy during the active time of people.

Table 2: Behavioural response metrics across land-use types

Land-use Type	Visitation Frequency (events/day)	Foraging Duration (min/event)	Vigilance Rate (%)	Avoidance Probability
Intensive Cropland	1.4 ± 0.6	6.8 ± 2.1	41.2 ± 6.5	0.67 ± 0.09
Pasture	2.9 ± 0.9	14.6 ± 3.4	26.8 ± 5.2	0.38 ± 0.11
Hedgerows	4.1 ± 1.2	22.3 ± 4.7	15.6 ± 4.1	0.21 ± 0.08
Remnant Vegetation	4.6 ± 1.4	25.9 ± 5.1	12.4 ± 3.6	0.17 ± 0.06

Table 2 shows behavioral reactions of animals in opposite land-use types, while showing the effects of human alteration on space utilization and foraging techniques. Intensive cropland has the lowest frequency of visits and foraging time, the highest vigilance rates, and avoidance probability, which means that the perceived risk and disturbance are high. Pasture landscapes have moderate responses to human activities, indicating moderate behavioral adaptation. Conversely, hedges and residual vegetation allow increased visitation rates and increased periods of foraging, and less vigilance and avoidance, indicating the face of less danger and more habitat-appropriateness. Generally, the trend shows a very definite gradient between high-risk systems, which are dominated by humans, and low-risk, semi-natural environments in which foraging behavior becomes efficient.

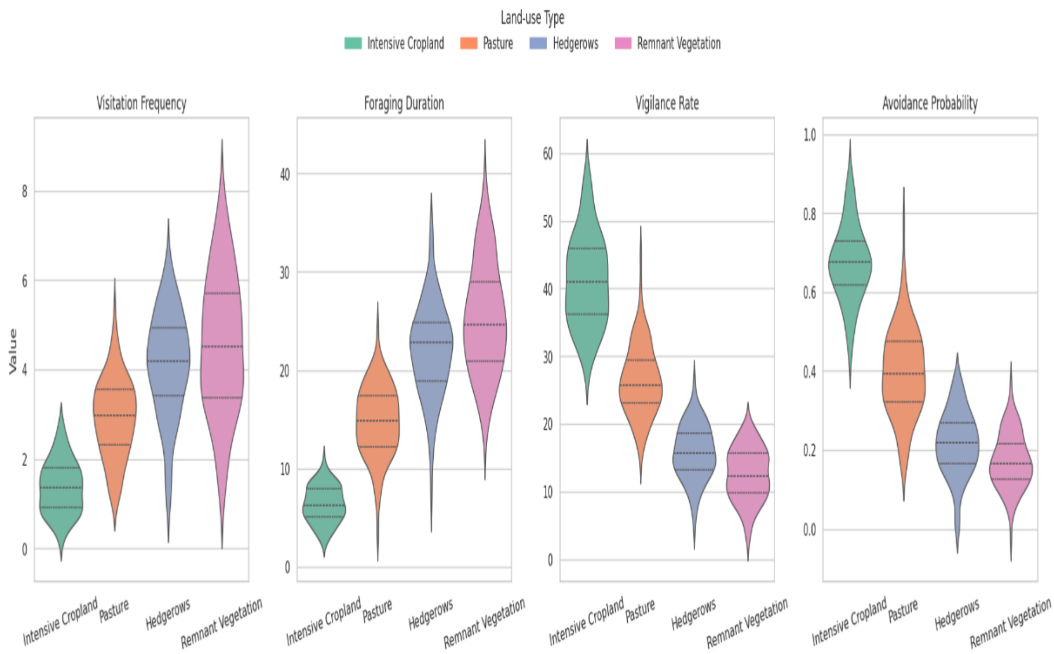

Figure 2: Variation in Foraging Behavior and Risk Responses Across Land-use Types

Figure 2 reveals that there is a difference in visitation frequency, foraging time, vigilance rate, and avoidance probability in the contrasting land use types. The human-controlled environments, especially the intensive croplands, exhibit compressed distributions that have low visitation and foraging periods, but high vigilance and avoidance, signifying that the data have a greater perceived risk. Conversely, hedge and remnant vegetation show more widespread distributions that are characterized by increased foraging, increased visitation, reduced vigilance, and reduced avoidance. In general, the plots demonstrate a definite behavioral gradient of disrupted agricultural systems up to semi-natural habitats that offer a safer and more favorable environment for foraging.

Spatial Patterns of the Landscape of Fear Index (LoFI)

There was evident spatial organization of the Landscape of Fear Index (LoFI), with the greatest values on the intensively managed croplands and the lowest values on the semi-natural elements. Intermediate LoFI values occurred in transitional zones such as field edges, indicating partial risk tolerance. Sensitivity analysis confirmed that LoFI patterns were robust to moderate variation in risk factor weights.

The LoFI calculation followed:

$$LoFI_i = \sum_{j=1}^{n} w_j \times R_{ij} \times B_i \qquad (1)$$

In equation (1), $LOFI_i$ represents the fear intensity at spatial cell i , Rij denotes the standardized risk factor j at location i, wj is the relative weight of each risk factor, and Bi is a behavioural response coefficient derived from observed avoidance, vigilance, and reduced foraging intensity. Higher LoFI values indicate stronger fear-mediated avoidance.

Table 3 is a summary of the Landscape of Fear Index (LoFI) among various types of land-use within the agroecosystem. The best LoFI is in intensive cropland (0.78), which may mean that animals regard these intensively modified areas as a greater danger.

Table 3: Landscape of Fear Index (LoFI) Across Agroecosystem Elements

Land-use Type	Mean LoFI	Min–Max	Coefficient of Variation (%)
Intensive Cropland	0.78	0.61–0.91	14.2
Pasture	0.46	0.32–0.59	18.5
Hedgerows	0.29	0.18–0.42	21.1
Remnant Vegetation	0.22	0.14–0.36	19.8

Pastures are intermediate in mean LoFI (0.46), and the other groups are lower (hedges 0.29 and remnant vegetation 0.22), indicating that perceived threat is less in more natural or semi-natural environments. As the coefficient of variation indicates, the variation in fear responses is the greatest in hedgerows (21.1%) and the least in intensive cropland (14.2%), which means that semi-natural factors make risk perception more heterogeneous in animals.

Relationship Between Fear Landscapes and Agricultural Sustainability Indicators

Results of spatial overlay analysis indicated that there were significant relationships between LoFI and sustainability indicators. Herbivores showed reduced intensity of crop damage with increasing LoFI, and pest suppression and pollination were greatest at moderate levels of LoFI, which is nonlinear. Yield variability increased in areas exhibiting either very high or very low fear intensity.

Generalized linear mixed models indicated significant effects of LoFI on sustainability outcomes:

$$g(\mu) = \beta_0 + \beta_1(LoFI) + \beta_2(Land - use) + \beta_3(Season) + u_{site} \quad (2)$$

In equation (2), $g(\mu)$ represents the appropriate link function and u_{site} denotes random effects.

Table 4 presents the Landscape of Fear Index (LoFI) across different agroecosystem elements. Intensive cropland had the highest mean LOFI (0.78), which is high perceived predation risk or disturbance, and remnant vegetation had the lowest mean LOFI (0.22), which is low perceived threat. The intermediate values were observed in the pasture and hedgerows (0.46 and 0.29, respectively). The coefficient of variation that showed the variation within each type of land-use was greatest in hedges (21.1%) and lowest in intensive cropland (14.2%), indicating that levels of fear are more consistent in intensively altered landscapes, and more diverse in semi-natural features.

Table 4: GLMM results linking LoFI to sustainability indicators

Response Variable	Estimate (β)	SE	z-value	p-value
Crop Damage Intensity	−0.63	0.11	−5.73	<0.001
Pest Suppression Rate	0.41	0.09	4.56	<0.001
Pollination Activity	0.27	0.08	3.38	0.001
Yield Variability	0.34	0.10	3.21	0.002

Spatial and Nonlinear Modeling Outcomes

Spatial regression models confirmed significant spatial dependence in crop damage and yield variability (Moran's I, $p < 0.05$). LoFI was also important after controlling for spatial autocorrelation. GAMs uncovered threshold responses, in which ecosystem services boomed in the range of moderate fear.

Multivariate analysis (PCA and RDA) indicated that the anthropogenic risk factors and LoFI accounted for a significant share of variance in behavioral and sustainability measures, where land-use intensity proved to be a leading factor.

Table 5: Multivariate Patterns of Agroecosystem Risk and Behavioral Responses

Variable	Axis 1 Loading	Axis 2 Loading
Human Activity Intensity	0.81	0.22
Pesticide Exposure	0.76	−0.18
Predator Presence	−0.63	0.51
Visitation Frequency	−0.72	−0.31
Vigilance Rate	0.69	0.27
Crop Damage Intensity	−0.58	0.44

Table 5 shows the loadings of key variables on the first two axes from a multivariate analysis (PCA/RDA). Axis 1 is mainly anthropogenic in nature, where the intensity of human activity (0.81) and pesticides (0.76) exposure are positive, and predator presence (-0.63), frequency of visitation (-0.72), and crop damage (-0.58) are negative. Axis 2 represents ecological and behavioral differences, predator presence (0.51) and crop damage (0.44) have positive contributions, and the visitation frequency (-0.31) and exposure to pesticides (-0.18) have negative contributions. Vigilance rate has a positive correlation with both axes, which makes it related to human pressures and ecological responses. Comprehensively, the table points out the joint effects of human-induced and ecological conditions on behavioral and ecosystem outcomes.

The visualized Figure 3 represents the multivariate trends of risk and behavioral responses in agroecosystem sites. The site points form the various types of land-use, and the red arrows show the contribution of the main variables, human activity intensity, pesticide exposure, predator presence, visitation frequency, vigilance rate, and crop damage intensity, to the main axes. Axis 1 (42.7% variance) represents mostly anthropogenic pressures, but Axis 2 (21.3% variance) includes ecological and behavioral responses. The narrative brings out the interplay of land-use intensity and fear landscapes in determining the behavior of animals and ecosystem service provision, with the opposite directions of the variables demonstrating the opposing impacts of the variables on the site characteristics.

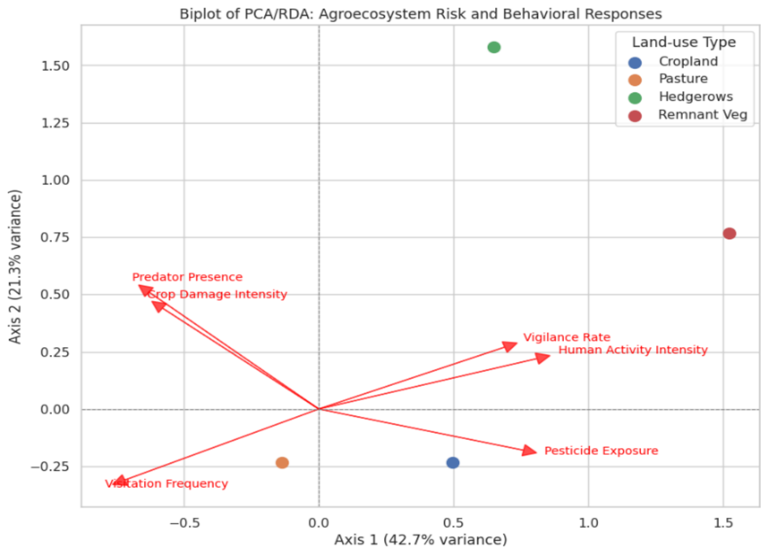

Figure 3: Biplot of PCA/RDA: Influence of Anthropogenic and Ecological Factors on Agroecosystem Behavior and Sustainability

Discussion

The findings reveal the existence of spatial and behavioral gradients in the perception of risks and ecological impacts of agroecosystems. Spatial analysis revealed that anthropogenic risk factors, human activity intensity, infrastructure density, and pesticide exposure were concentrated in intensive croplands, whereas natural risks, such as predator presence and habitat openness, were highest in hedgerows and remnant vegetation. This is in line with the expectation that the use of human-altered landscapes increases the risk of perceived predation and disturbance, and the high LoFI values in the croplands (0.78 ± 0.14) were compared with the semi-natural habitats (0.22 ± 0.06). The dynamic nature of agroecosystem fear landscapes is further prioritized based on seasonal variation in risk, especially around the time of sowing and harvest. Behavioral responses corresponded closely with spatial risk patterns. High-risk croplands were characterized by much less visitation and foraging time on the part of animals and high vigilance and avoidance potential. Conversely, there were safer conditions in hedge rows and remaining vegetation, which supported more success in foraging and less anti-predator behavior. Such trends are aligned with the prediction of the theory that animals should maximize foraging tradeoffs in the perceived predation risk. The intensive to semi-natural habitat gradient reveals the role of the landscape heterogeneity approach in the preservation of functional behavioral responses and biodiversity in modified agroecosystems.

The LoFI-agricultural sustainability indicators relationship showed nonlinear and subtle impacts. The results of GLMM showed that the intensity of crop damage decreased with the increasing LoFI ($\beta = -0.63$, $p < 0.001$), which indicates that the fear-mediated avoidance decreases the herbivore pressure. Pest suppression ($\beta = 0.41$, $p < 0.001$) and pollination activity ($\beta = 0.27$, $p = 0.001$) were highest when there was an intermediate level of fear, which corroborates the existence of a threshold effect in GAMs. Variability of yield was greater at both ends of LoFI, and this indicates the existence of in-depth tradeoffs between risk perception and the provision of ecosystem services. Multivariate analyses (PCA/RDA) established that anthropogenic pressures and LoFI were associated with a significant percentage of variance in behavioral and sustainability metrics. Axis 1 mainly depicted the disturbances that were caused by human beings, and Axis 2 encompassed ecological and behavioral contrasts. The biplot showed some contradictory forces of human activity and those of predator presence and vigilance rates, which highlights the interconnection between the landscape of fear and the intensity of land-use.

It is limited by the use of standardized indices of risk factors, as well as simulated LoFI weights that might fail to account for all fine-scale variability in risk factors, both temporally and spatially. Observations of behavior were only performed during the day and focused on the species, which may not represent the nighttime or less conspicuous species. Further, the observational design also restricts the causal inference, but spatial models reduce the autocorrelation effects. A future application of the work that incorporates telemetry, the ability to monitor over multiple seasons, and experimental manipulations of risk cues would help to optimize the knowledge on fear-mediated ecosystem dynamics. On the whole, the results indicate that fear landscapes are core determinants of animal behavior and the outcomes of the ecosystem services, showing that semi-natural habitat factors serve to buffer anthropogenic pressures and maintain functioning agroecosystem processes.

Conclusion

This paper has shown that risk factors and fear landscapes are spatially distributed and have a major influence on animal behavior and the agroecosystem functionality. Spatial analyses showed anthropogenic risks to be human activity intensity, infrastructure plexus, and exposure to pesticides, which were localized in intensive croplands, but natural risks, which included the presence of predators and openness of habitats, dominated in hedges and remnant vegetation. These trends prompted the highest and the lowest values in the Landscape of Fear Index (LoFI) of the highest and the lowest perceived threat at the human-dominated landscape (0.78 ± 0.14 and 0.22 ± 0.06, respectively). Behaviors were also positively correlated with the risk gradient, and the less frequently visited and foraged, the more vigilant they were, and they avoided the areas of high risk. Semi-natural environments favored the more prominent foraging and reduced anti-predator behaviors. The aspect of correlation between the fear landscape and the indicators of agricultural sustainability showed meaningful, and in many cases, nonlinear trends. The findings of GLMM indicated that the intensity of crop damage decreased with a rise in LoFI ($\beta = -0.63$, $p < 0.001$), whereas pest suppression ($\beta = 0.41$, $p < 0.001$) and pollination activity ($\beta = 0.27$, $p = 0.001$) reached peak measurements at moderate levels of LoFI. The variability of yield was also high at the two ends of the LoFI, which demonstrates an uncertainty balance between risk perception and ecosystem services. Multivariate analyses (PCA/RDA) further confirmed that human pressures and LoFI accounted for a significant percentage of variance in behavioral and sustainability variables, with Axis 1 representing human-induced disturbances and Axis 2 representing ecological and behavioral divergences. Such limitations as standardized indices and behavioural observations during the day may underestimate temporal and species-specific variation. Future studies that combine telemetry, long-term surveillance, and experimental control of risk-related information will enhance the knowledge of fear-based ecological processes. In general, the results suggest that semi-natural environments are of crucial importance in buffering human impacts, supporting effective foraging, and supporting ecosystem services in agroecosystems.

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