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SYSTEMATIC REVIEW

Technological Innovations in Raptor Conservation: A Systematic Review of Methods and Applications

Innovaciones Tecnológicas en la Conservación de Aves Rapaces: Una Revisión Sistemática de Métodos y Aplicaciones

Gonzalo Espinosa[1], Julio Guerra[2], Francisco Naranjo[2], Luis Mosquera[2]

[1]Universidad Estatal Amazónica. Zamora Chinchipe, Ecuador.
[2]Universidad Técnica del Norte. Ibarra, Ecuador.

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Corresponding author: Francisco Naranjo

ABSTRACT

Introduction: raptors play a critical role in ecosystem stability, yet many species face significant population declines due to habitat loss, climate change, and human-induced mortality. Technological advancements such as satellite telemetry, machine learning, bioacoustics, and radar tracking have transformed raptor research, enabling precise monitoring and data-driven conservation strategies.
Method: a systematic review using the PRISMA methodology was conducted on the most relevant methodologies and technologies used in raptor research. Data from multiple studies employing satellite telemetry, habitat modeling, genetic analysis, bioacoustics, and conservation management tools were synthesized to evaluate their effectiveness.
Results: findings indicated that satellite telemetry remains the most widely used tool for tracking raptor movements, while machine learning and bioacoustics are emerging as powerful methods for habitat assessment. Population viability models frequently overlook key demographic factors, such as the age of first breeding, which can significantly impact conservation outcomes.
Conclusions: integrating advanced technologies with standardized methodologies is essential for improving raptor conservation. Future research should focus on refining predictive models, enhancing data-sharing platforms, and ensuring technological advancements translate into effective conservation policies.

Keywords: Raptors; Satellite Telemetry; Habitat Modeling; Conservation Strategies; Population Viability.

RESUMEN

Introducción: las aves rapaces desempeñan un papel fundamental en la estabilidad de los ecosistemas, pero muchas especies enfrentan un declive poblacional significativo debido a la pérdida de hábitat, el cambio climático y la mortalidad inducida por el ser humano. Los avances tecnológicos como la telemetría satelital, el aprendizaje automático, la bioacústica y el rastreo por radar han revolucionado la investigación sobre rapaces, permitiendo un monitoreo preciso y estrategias de conservación basadas en datos.
Método: se realizó una revisión sistemática utilizando el método PRISMA para estudiar las metodologías y tecnologías más relevantes utilizadas en la investigación de rapaces. Se sintetizaron datos de múltiples estudios que emplearon telemetría satelital, modelado de hábitat, análisis genético, bioacústica y herramientas de manejo.
Resultados: los resultados indicaron que la telemetría satelital sigue siendo la herramienta más utilizada para el rastreo de movimientos de rapaces, mientras que el aprendizaje automático y la bioacústica están emergiendo como métodos prometedores para la evaluación del hábitat. Los modelos de viabilidad

poblacional a menudo omiten factores demográficos clave, como la edad de primera reproducción, lo que puede afectar significativamente los resultados de conservación.
Conclusiones: la integración de tecnologías avanzadas con metodologías estandarizadas es fundamental para mejorar la conservación de las rapaces. La investigación futura debe centrarse en refinar modelos predictivos, mejorar plataformas de intercambio de datos y garantizar que los avances tecnológicos se traduzcan en políticas de conservación efectivas.

Palabras clave: Rapaces; Telemetría Satelital; Modelado de Hábitat; Estrategias de Conservación; Viabilidad Poblacional.

INTRODUCTION

Raptors, or birds of prey, are a diverse group of avian predators characterized by sharp talons, powerful beaks, and exceptional hunting abilities. These birds play an important role in maintaining ecological balance by regulating prey populations and serving as bioindicators of ecosystem health. However, global raptor populations face increasing threats due to habitat loss, climate change, human-wildlife conflicts, and exposure to environmental contaminants.[1] Recent studies indicate that nearly a fifth of all raptor species are at risk of extinction, underscoring the urgent need for innovative research and conservation strategies.[2]

Advancements in technology have revolutionized raptor research, enabling more precise monitoring and data collection. Satellite telemetry, machine learning, bioacoustics, and radar systems have provided unprecedented insights into raptor movements, habitat preferences, and mortality risks.[3] These tools have significantly improved conservation efforts by identifying critical habitats, migration corridors, and anthropogenic threats such as wind farms and habitat fragmentation.[4] However, challenges remain in standardizing methodologies, ensuring data accuracy, and making technology accessible to conservation practitioners in diverse geographic regions.

Despite technological progress, discrepancies persist in the applicability and transferability of habitat suitability models across different ecosystems. For example, research on the Mexican spotted owl (Strix occidentalis lucida) revealed significant variations in habitat preferences between forested and rocky canyonland environments, emphasizing the need for localized, scale-optimized models.[5] Similarly, reintroduction programs have demonstrated that neglecting critical demographic parameters—such as the age of first breeding—can severely impact population viability models.[6] These findings highlight the importance of effectively refining conservation models to integrate ecological, demographic, and environmental variables.

This study aims to critically analyze the methodologies and technologies currently employed in raptor research, evaluating their effectiveness, limitations, and applicability to conservation planning. By synthesizing data from diverse studies, the research aims to bridge the gap between technological innovation and practical conservation strategies. The study seeks to provide a comprehensive assessment of the tools available for raptor monitoring, habitat modeling, and population management, ultimately contributing to developing more efficient and globally applicable conservation frameworks.

METHOD

This systematic review follows a structured approach to identify and analyze scientific literature related to the conservation of raptors and the technologies applied to their monitoring and management. The Scopus database was used as the primary source for retrieving peer-reviewed articles. Three distinct search queries were formulated to capture different aspects of raptor conservation and technological advancements:

1. (raptors OR “birds of prey”) AND (conservation AND technology)
2. (“satellite telemetry” OR “tracking devices”) AND (raptors OR “birds of prey”)
3. ((habitat AND management) OR reintroduction) AND (raptors OR “birds of prey”)

Inclusion and Exclusion Criteria

After retrieving the records from Scopus, a multi-step screening process was conducted to refine the selection of articles. The following criteria were applied: Inclusion Criteria: peer-reviewed journal articles published in English, studies focused on the use of technology in raptor conservation, tracking, and habitat management, and research presenting novel methodologies, models, or advancements in conservation strategies.

Exclusion Criteria: Non-peer-reviewed publications, such as conference proceedings, book chapters, and grey literature, studies that did not explicitly focus on raptors and articles without direct relevance to technological applications in raptor conservation.

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Data Collection and Processing

For each search criterion, the number of records retrieved at different stages of screening was recorded and visualized (figure 1). The data screening process included: Initial Identification, where articles were selected based on title, abstract, and keywords; Screening Phase, in which duplicates were removed and articles were assessed for relevance; and Full-Text Retrieval, where articles meeting inclusion criteria were obtained for full review; and Final Selection, in which only the studies that met all eligibility criteria were included in the final analysis.

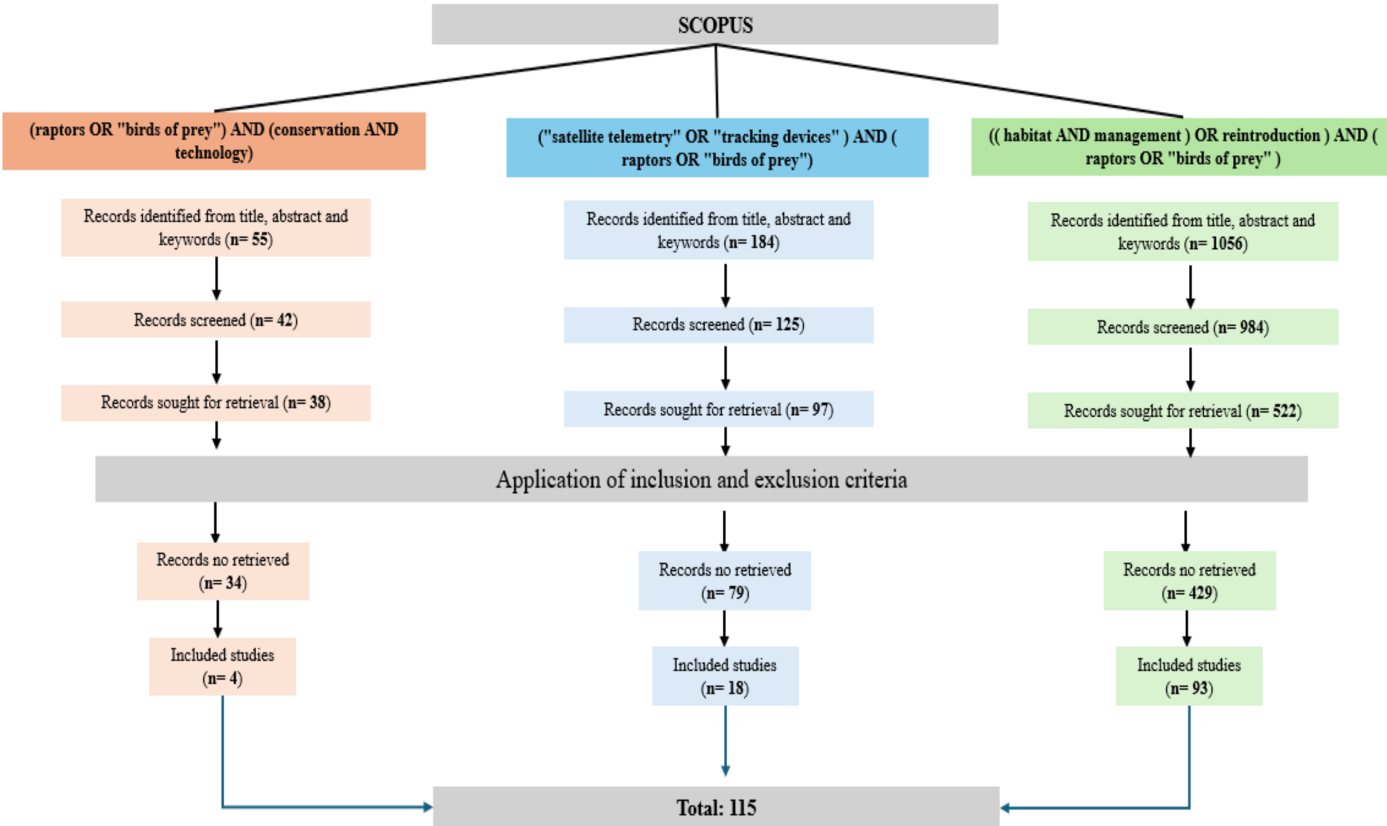

Figure 1. Prisma Flow Chart

The systematic search yielded a total of 1 295 records, with the distribution as shown in table 1.

Table 1. Distribution of the records

Search Criteria	First record	Included articles
(raptors OR "birds of prey") AND (conservation AND technology)	55	4
("satellite telemetry" OR "tracking devices") AND (raptors OR "birds of prey")	184	18
((habitat AND management) OR reintroduction) AND (raptors OR "birds of prey")	1056	93

After applying the inclusion and exclusion criteria, 115 studies were included in this systematic review. Based on the abstracts analyzed, four major categories of technological methodologies were identified (table 2).

The selected studies were analyzed based on their methodologies, technological innovations, and contributions to raptor conservation. Key aspects such as tracking technologies, habitat management models, reintroduction strategies, and climate change adaptation were synthesized to provide a comprehensive overview of the field's current state.

Table 2. Studies included in the systematic review

Type	References	Total of articles	Subtypes
Technologies	(2-4,7-38)	35	Drones, Camera Trap, VHF, Autonomous Recording Units (ARUs), Airborne laser scanning (ALS), Avian translocations, FLUS, Satellite telemetry, GPS, and tracking technologies.
Digital Resources	(1,39-43)	6	Software, Digital Platform and APIs.
Techniques	(44-52)	9	Hacking, Kaplan-Meier, Text Mining, Nest Models, doble clutching, Photography and Post Construction Fatality Tracking (PCFM)
Models / methodologies	(5,6,53-116)	65	Bayesian Model, Multinomial Discrete Choice Models, Generalized Linear Models (GLM), Generalized Linear Mixed Model (GLMM), Fixed Loss Rate (FLR), Linear Mixed Model (LMM), Mixed Cumulative Link Model, Brownian Bridge Model, Logistic Regression Models, Geographic Information System, Random Model, Random Forest Models, Habitat Models, Population Models, Species Distribution Models, Multi-state Models, Generalized Additive Mixed Models (GAMM), Algorithmic Model, Reintroduction, IAM and TPM Models, Step Selection Functions (SSF), Machine Learning Model, Mixed Effects Models, Generalized Estimating Equations (GEE), Ecological Niche Modeling, Maximum Entropy Model (MAXENT), Capture-Mark-Recapture (CMR) Models, Generalized Linear Model and Non-Metric Multidimensional Scaling (NMDS), Structural Equation Models (SEM), Feeding Models (Diets), Matrix Models, Sampling, Noise Model, Foraging Pattern

RESULTS

Technological and Methodological Approaches in Raptor Conservation Studies

A systematic review of scientific literature on raptor conservation identified a range of technological methodologies applied to monitoring, habitat modeling, and species management. The primary methods used include text mining, Bayesian hierarchical models, generalized linear models (GLMs), satellite telemetry, step selection functions (SSFs), dynamic Brownian bridge models (dBBMM), and machine learning approaches. Each methodology provides distinct advantages and limitations depending on the conservation objective.

Text Mining in Avian Migration Research

Text mining is a powerful tool for identifying emerging research trends in avian migration studies. It enables researchers to process large datasets with minimal subjectivity.[117] The ability to extract patterns from unstructured textual data enhances priority setting in conservation efforts. However, text mining is limited by the quality and completeness of the literature analyzed, as it relies on metadata rather than direct field observations.

Bayesian Hierarchical Models for Reproductive Success Analysis

Bayesian hierarchical modeling has proven effective in estimating individual and population-level reproductive success using movement data. Satellite telemetry and infrequent breeding surveys have been used to infer reproductive probabilities and spatial dynamics in golden eagles.[116] These models offer robust statistical inferences but are computationally demanding and require detailed prior information, limiting their applicability in regions with scarce population data.

Generalized Linear Models (GLMs) and Logistic Regression for Habitat Modeling

GLMs, particularly logistic regression within GIS frameworks, are used to predict species distributions. For example, the wintering habitat of Oriental Honey Buzzards was modeled using logistic regression with GPS tracking data, highlighting the importance of selecting pseudo-absence data to minimize commission and omission errors.[87] While GLMs provide interpretable results, they are often less flexible than machine learning models when dealing with complex, high-dimensional datasets.

Satellite Telemetry and Dynamic Brownian Bridge Models (dBBMM) for Space-Use Analysis

Satellite telemetry remains one of the most versatile and widely applied tools in raptor conservation, enabling fine-scale movement tracking. dBBMM has been particularly useful in assessing space-use patterns of species such as the white-tailed eagle within Natura 2000 protected areas.[91] This methodology improves movement pathway estimates by incorporating spatial autocorrelation, yet it requires high-frequency GPS data, which may be limited by device constraints or energy consumption.

Machine Learning and Habitat Suitability Models

Machine learning techniques, including random forest models and Maxent modeling, have been increasingly used in habitat suitability predictions. The Maxent model has been applied to raptors to predict species distribution based on environmental variables and human disturbance factors.(53) Despite its strengths in handling presence-only data, Maxent requires a careful selection of predictor variables to avoid overfitting and misinterpreting habitat suitability projections.

Step Selection Functions (SSFs) and Movement Ecology

Advanced spatial modeling techniques, such as step selection functions (SSFs), have been integrated with satellite telemetry to examine habitat selection in response to anthropogenic features. The el-SSFs method has been used to quantify the impact of linear infrastructures on raptor migrations, revealing that man-made structures significantly alter migration corridors.(21) While SSFs provide detailed insights into movement behavior, they are data-intensive and may not effectively capture long-term habitat selection trends.

Population Viability Analysis (PVA) and Reintroduction Strategies

PVA remains a cornerstone in raptor conservation, particularly in reintroduction programs. A study on Spanish Imperial Eagles and Ospreys demonstrated that reducing the age of first breeding improves reintroduction success. However, many PVAs fail to account for density-dependent breeding variables.(6) While PVA provides quantitative risk assessments, its accuracy depends on data availability, making it less reliable for newly established populations.

Below, the most relevant studies are presented in table 3, highlighting their methodologies and key findings in raptor research.

Table 3. Most relevant studies

Article	Authors	Models or methodology	Description	Year
Identifying research trends in avian migration tracking in Korea using text mining(117)	Seok-Jun Son, Min Seock Do, Green Choi, Hyung-Kyu Nam	Text mining	The article utilizes text mining to analyze research trends in avian migration tracking in Korea. Abstracts from 64 scientific articles were processed, extracting frequent keywords such as "home," "range," "breeding," "wintering," "island," "area," and "habitat." This technique allowed for the identification of patterns and correlations in the literature, minimizing subjectivity and helping to visualize emerging trends in the study of bird migration routes	2023
A hierarchical modelling framework for estimating individual- and population- level reproductive success from movement data (116)	Joseph M. Eisaguirre, Perry J. Williams Christopher P. Barger, Julia C. Brockman, Greg A. Breed, Travis L. Booms, Stephen B. Lewis	Bayesian hierarchical model that estimates the probability of an animal producing offspring from movement data	This study develops a Bayesian hierarchical model to estimate reproductive status using satellite telemetry data and infrequent breeding surveys. Applied to migratory golden eagles (Aquila chrysaetos) in Alaska, the model infers movement behavior, space use, reproductive success probability, and covariate effects. It scales from individuals to populations, capturing interannual variability. Though tested on raptors, the method is generalizable to other taxa.	2023
Modeling the Wintering Habitat Distribution of Oriental Honey Buzzards in West Java Indonesia with Satellite Tracking Data Using Logistic Regression(87)	Syartinilia	logistic regression (LR) analysis coupled with GIS	This study highlights generalized linear models (GLMs), particularly logistic regression within GIS, as a preferred method for predicting species distributions. A key challenge is determining presence and absence data, especially when using satellite tracking data, which provides abundant presence records. Special attention is required in generating pseudo-absence data to minimize commission and omission errors, ensuring model accuracy.	2021
Golden Eagle Populations, Movements, and Landscape Barriers: Insights from Scotland (19)	Alan H. Fielding	GET model using the tool of satellite telemetry	This study utilizes GPS satellite tracking to investigate golden eagle (Aquila chrysaetos) movement patterns across different scales and life stages, focusing on geographical barriers affecting range expansion and population isolation. Using over seven million dispersal records from 152 nestlings, the study identifies lowland terrestrial habitat and large water expanses as significant movement barriers, validating sub-population differentiation in Scotland. Findings support the South Scotland Golden Eagle Project (SSGEP) and predict potential re-colonization of England. The study underscores the importance of combining genetic, demographic, and movement data for conservation planning.	2024

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GPSTracking Reveals the White-Tailed Eagle Haliaeetus albicilla as an Ambassador for the Natura 2000 Network [91]	Probst R, Schmidt M	Dynamic Brownian bridge motion models (dBBMM)	This study evaluates the role of the Natura 2000 network in the natal dispersal of Austrian-hatched white-tailed eagles (Haliaeetus albicilla) using 907,466 GPS locations from 38 individuals analyzed with a dynamic Brownian Bridge Movement Model. The findings show that 67 % of the 50 % isopleth overlaps with Natura 2000 sites, indicating a high probability of eagle utilization. The eagles predominantly used wetlands, waterbodies, and adjacent deciduous forests, while avoiding coniferous forests and settlements. Anthropogenic mortality was low within protected areas, reinforcing the importance of Natura 2000 for conserving this top predator throughout its life stages.	2024
Dynamics in spatial use by Ospreys (Pandion haliaetus) during the breeding season revealed by GPS tracking [22]	Bernd Ulrich Meyburg	Generalized additive mixed models (GAMMs) on home range size (KDE95) with telemetry data	This study investigates breeding-area movement behavior of Ospreys (Pandion haliaetus) using solar-powered GPS satellite telemetry on 17 adults in northeast Germany tracked for up to seven years. Home range size varied by sex, nesting site, and breeding success, with breeding males (median 33,4 km^2) having significantly larger ranges than females (median 4,6 km^2). Some females made long excursions post-fledging, while males maintained consistent home ranges with water surfaces comprising 9,6–29 % of their territories. Overnight roost distances were significantly correlated with female home range size but not males. Males using the same nests in different years showed 37,3–54,7 % home range overlap, often incorporating different waterbodies	2023
Wind effects on the long-distance migration of GPS-tracked adult ospreys Pandion haliaetus from Germany [52]	Bernd-Ulrich Meyburg	Telemetry data and GLMM generalized binomial mixed effects models	This study applies generalized linear mixed models (GLMMs) to analyze how orientation behavior depends on region and distance to the next target using detailed GPS tracking data from repeated trips over multiple years. The analysis identifies intermediate targets, including stopover sites and high-traffic areas. Solar-powered GPS PTTs recorded hourly high-accuracy positions, providing valuable insights into movement patterns and migratory navigation.	2023
Search Foraging Strategies of Migratory Raptors Under Different Environmental Conditions [25]	Javier Vidal-Mateo	Lévy and the Brownian random search Using telemetry data	This study examines movement patterns of four migratory raptor species—Egyptian Vulture, Short-toed Snake Eagle, Booted Eagle, and Red Kite—to assess how search strategies vary by species and season. Using GPS tracking data, movements were analyzed for Lévy and Brownian random search patterns. The Egyptian Vulture shifted between both patterns in the breeding season but primarily used Brownian search in winter, while the Short-toed Eagle followed a Lévy pattern year-round. The Booted Eagle and Red Kite combined strategies, adapting to resource availability. These findings suggest that diet specialization influences movement, with Lévy searches optimizing encounters with scarce resources, while generalist feeders adjust based on abundance	2022
Extensive dune grasslands largely lacking human disturbance are an important refuge for a vole-dependent raptor [100]	Steffen K Ampfer	Generalized linear mixed-effects models (GLMMs) with binomial error structure	This study investigates habitat preferences of the Short-eared Owl (Asio flammeus) in its last permanent breeding area in Germany (East Frisian Islands). Based on 576 territories across six islands and 13 nest-site analyses on Spiekeroog, results show a strong preference for open dunes, particularly dune grasslands, while avoiding built-up areas and tree stands. Nest sites favored tall, dense vegetation with high herb and litter cover, enhancing concealment and microclimate stability. Surrounding areas featured shorter vegetation with litter, improving fledgling mobility, vole abundance, and prey accessibility. The study underscores the importance of extensive open grasslands with minimal human disturbance for conservation efforts.	2023

Multiscale habitat suitability modeling for a threatened raptor offers insight into ecological model transferability [5]	Nayeri D, Cushman S	habitat suitability model optimized for scale	This study examines habitat use differences in the Mexican Spotted Owl (Strix occidentalis lucida, MSO) between forests and rocky canyonlands, addressing non-stationarity in species-habitat preferences. Using an ensemble-based habitat suitability model for rocky canyonlands, the study identifies slope, cumulative degree days, insolation, and monsoon precipitation as key environmental factors. Comparisons with a forest-based model reveal that canopy cover and mixed-conifer presence are more relevant in forests. The forest model performed poorly in canyonlands, predicting low suitability even in known nesting areas, confirming habitat-specific differences.	2024
The role of age of first breeding in modeling raptor reintroductions [6]	Virginia Morandini	Population viability analysis (PVA)	This study examines the role of age of first breeding in population viability analysis (PVA) for reintroduced populations, focusing on Spanish Imperial Eagles (Aquila adalberti) and Ospreys (Pandion haliaetus) in southern Spain. Using simulations based on wild and reintroduced populations, results show that reducing the age of first breeding is critical for reintroduction success, as it enhances population growth and resilience. Ignoring density-dependent variation in breeding age underestimates population viability, limiting the model's ability to predict responses to density fluctuations. The study underscores the need to integrate breeding age variability in PVA models for long-lived birds with deferred maturity.	2019
Maxent modeling for predicting the spatial distribution of three raptors in the Sanjiangyuan National Park, China [53]	Zhang J, Jiang F	Maximum entropy model (MaxEnt)	This study applies the Maximum Entropy Model (Maxent) to predict habitat suitability using environmental variables and species presence points. Maxent is widely used in niche modeling due to its ability to generate accurate predictions with limited data. The model incorporates elevation, climate, and human disturbance as key factors influencing species survival and reproduction, with elevation emerging as the most critical variable affecting habitat suitability for the three studied species.	2019
Landscape heterogeneity affects diurnal raptor communities in a sub-tropical region of northwestern Himalayas, India [104]	Kumar S, Sohil A	Generalized linear model and non-metric multidimensional scaling (NMDS)	This study examines diurnal raptor assemblages and seasonality in a subtropical habitat of India's northwestern Himalayas over a two-year survey (2016–2018) across 33 sites. Observing 3,434 individuals from 28 species, results show significant habitat- and season-dependent variations in species richness and abundance, with farmlands and winter seasons being the most diverse. A generalized linear model (GLM) identified elevation and proximity to dumping sites as key factors influencing raptor abundance, while non-metric multidimensional scaling (NMDS) revealed distinct raptor assemblages across habitats. The study underscores the high conservation value of forest patches and farmlands, emphasizing the need for targeted conservation measures.	2022
Raptor resource use in agroecosystems: cover crops and definitions of availability matter [88]	Megan E. Zagorski	Random models and logistic regression models	This study employs resource selection functions (RSFs) within a use-availability framework to assess raptor habitat using weighted logistic regression models at two spatial scales (transect and landscape). Habitat availability was defined using two approaches: completely random points and random points with perch restrictions. The random models identified potential perch sites, while the restricted random models revealed finer-scale habitat preferences not detected in the fully random approach, improving the understanding of habitat selection in raptors.	2021

The diversity of methodologies applied to raptor conservation shows the complexity of conservation challenges. While traditional statistical models (e.g., GLMs, logistic regression) continue to be widely used, integrating machine learning, Bayesian statistics, and step selection modeling offers greater predictive accuracy

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and ecological insight.

Technologies Used in Raptor Research

The development of tools such as satellite telemetry, drones, artificial intelligence, and molecular analysis has revolutionized how data on these species are collected and analyzed.

Satellite Telemetry and GPS: The Foundation of Raptor Research

Satellite telemetry remains one of the most widely used technologies for studying raptor behavior, providing detailed information on migration, habitat use, and survival. Studies such as [33] documented the movement behavior of juvenile golden eagles in Mexico using satellite telemetry for the first time, demonstrating its great utility in studying poorly researched species.

Other studies have used GPS/GSM to analyze juvenile and adult dispersal, such as [4], who investigated the relationship between nest site affiliation and survival of white-tailed eagles in Denmark, Sweden, and Germany. These studies highlight the versatility of GPS for different purposes, from tracking migration routes to analyzing environmental interactions during specific life stages. However, telemetry comes with challenges. Studies like that of [36] evaluated the accuracy of altitude data obtained via GPS and barometric altimetry, highlighting the need for calibrations to avoid systematic errors in altitude data. This finding is crucial for modeling flight dynamics and habitat use in raptors.

Integration of Telemetry with Predictive Models and Remote Sensing

Combining telemetry with advanced statistical models has improved the interpretation of tracking data. For example, resource selection models have been used to evaluate raptor habitat use in agricultural landscapes, as seen in the work of [88], which employed weighted logistic regression models to assess perch availability and other key structures.

Additionally, integrating telemetry with avian radar has proven to be a promising tool for evaluating the synchronization of raptor movements with human infrastructure.[3] assessed airport radar systems to minimize bird-aircraft collision risks, demonstrating the effectiveness of combined monitoring technologies.

Drone Applications in Nest Monitoring and Behavior Studies

Drones have become a crucial tool in raptor research. For instance, Chavko[7] demonstrated how drones improved efficiency in locating imperial eagle nests in Slovakia, reducing the need for invasive field visits. Moreover, drones have been used in rehabilitation and training programs for raptors.[86] integrated them with falconry techniques to enhance the recovery of rescued raptors before their release.

Bioacoustics and Passive Monitoring

Bioacoustics has emerged as a promising tool for studying elusive raptor populations. Studies such as [118] have shown how autonomous recording units (ARUs) effectively monitor species like the spotted owl in U.S. forests.

Additionally, ARUs have been combined with machine learning algorithms like BirdNET, enhancing the identification of vocalizations in large acoustic datasets. These bioacoustic advancements significantly reduce the need for in-person monitoring while improving the efficiency of long-term studies.

Molecular and Genetic Methods

Genetic studies are important in raptor research, providing key insights into population structure, diet, and disease monitoring. Nourani[112] used molecular analyses to detect blood parasites in rehabilitated raptors in Iran, demonstrating the utility of these methods in assessing avian health.

Another significant advancement has been the use of HTS-based metabarcoding, as seen in the study by [118], which analyzed the diet of hen harriers in Great Britain using DNA extracted from chick buccal swabs. This method represents a major improvement over traditional pellet analysis, which is more prone to biases in prey identification.

Artificial Intelligence and Mathematical Modeling Applications

Artificial intelligence is becoming increasingly relevant in interpreting telemetry data. A novel example is the Blogging Birds system, developed by Siddharthan[40], This system generates automated narratives based on satellite tracking data of red kites in the UK, facilitating science communication. Meanwhile, mathematical models have been widely used to evaluate environmental impacts on raptor populations. Tsiakiris[43] applied a population viability analysis (PVA) model to assess the effects of poisoning on vultures, concluding that small but frequent poisoning events can be more damaging than large but rare ones.

Below, the most relevant studies are presented in table 4, highlighting their technologies, and key findings in raptor research.

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Table 3. Most relevant studies

Article	Authors	Technologies	Description	Year
Commentary: the Past, Present, and Future of the Global Raptor Impact Network[1]	McClure, Christopher J. W.	Global Raptor Impact Network (GRIN)	The Global Raptor Impact Network (GRIN) is an initiative aimed at enhancing collaboration and conservation efforts within the raptor research community. GRIN builds upon its predecessors, the African Raptor DataBank and the Global Raptor Information Network, to expand data collection and storage capabilities worldwide through a mobile application. It incorporates data-sharing protocols to protect sensitive species and allows users to mark records as confidential. The platform supports conservation assessments by analyzing species' population trends and distributions and provides systematic reviews, bibliographies, and species accounts. GRIN serves as a centralized resource for researchers, facilitating information exchange and collaboration to address raptor population declines in the Anthropocene.	2021
Home Ranges and Migration Routes of Four Threatened Raptors in Central Asia: Preliminary Results[15]	Ram, M.; Sahu, A.; Tikadar, S.; Gadhavi, D.; Más bien, TA; Jhala, L.; Zala,	Satellite telemetry	This study utilizes satellite telemetry to analyze the movement ecology, home range, and migration routes of four raptor species: Greater Spotted Eagle (*Clanga clanga*), Indian Spotted Eagle (*Clanga hastata*), Tawny Eagle (*Aquila rapax*), and Pallid Harrier (*Circus macrourus*). Home ranges were calculated using Minimum Convex Polygons (MCP) and Kernel Utilization Distributions (KUD), revealing significant variation among species. The Pallid Harrier exhibited the smallest home range (4,29 km^2 MCP, 3,98 km^2 KUD) in its Russian breeding ground, while the Greater Spotted Eagle had the largest (9331,71 km^2 MCP, 5991,15 km^2 KUD) in Kazakhstan. Migration distances increased significantly on a monthly and daily basis. This research provides the first documented home range of the Indian Spotted Eagle in Pakistan and confirms that tracked raptors prefer lower elevation flyways over the Himalayas rather than the direct northern routes. This is the first satellite telemetry study in the region, offering key insights into the migration patterns of raptors in India	2022
Monitoring Raptor Movements with Satellite Telemetry and Avian Radar Systems: An Evaluation for Synchronicity [3]	Washburn, B.E.; Maher, D.; Beckerman, S.F.; Majumdar, S.; Pullins, C.K.; Guerrant, T.L.	Combining bird monitoring/tracking technologies, such as satellite telemetry and avian radar, has the potential to provide unique insights into avian movements in local areas of interest	This study evaluates the effectiveness of X-band marine radar sensors in tracking *Buteo jamaicensis* (Red-tailed Hawks) at Chicago's O'Hare International Airport from 2010 to 2014, using satellite telemetry data for validation. The primary goal was to assess the synchronicity between radar-detected tracks and telemetry-confirmed locations, providing insight into the biological relevance of radar data for wildlife management in human-conflict zones such as airports and wind farms. Results showed a significant decline in radar detection capability as the distance between birds and sensors increased. Despite 1977 potential detection events, only 51 (2,6 %) were successfully tracked, indicating low synchronization.	2022
Distribution, abundance, and breeding of the imperial eagle (Aquila heliaca) in Western Slovakia in 1977–2022 [7]	Jozef Chavko , Leonidas Prešinský & Roman Slobodník	Drones	This study provides a comprehensive analysis of the distribution, abundance, breeding success, and habitat preferences of the Imperial Eagle (*Aquila heliaca*) in Western Slovakia over a 45-year period (1977–2022). A total of 65 breeding pairs were documented, with 589 breeding attempts recorded, of which 420 (74 %) were successful, resulting in 718 fledged chicks. Breeding success rates fluctuated annually, averaging 1,2 chicks per initiated attempt and 1,7 per successful attempt. The breeding population showed slow growth between 1977 and 1997, followed by a significant increase post-1998, with numbers more than doubling in 2020 and 2021. Since 2000, a shift in habitat preference from mountainous regions to lowland areas has been observed.	2022

CONCLUSIONS

The study underscores the growing significance of advanced technological methodologies in raptor research, conservation, and management. A critical analysis of various modeling approaches, tracking technologies, and

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data integration methods highlighted the strengths and limitations of contemporary tools applied to studying birds of prey. Integrating satellite telemetry, machine learning models, bioacoustics, and habitat suitability analyses has significantly improved our understanding of raptor movement patterns, habitat preferences, and threats. However, our findings also reveal inconsistencies in methodology standardization, particularly in the transferability of habitat models and the interpretation of remote sensing data.

The technological landscape for raptor research has evolved considerably, with satellite telemetry as a dominant tool, providing precise movement data across migratory and resident species. However, as demonstrated by comparative studies, the effectiveness of telemetry depends heavily on environmental conditions, species-specific behaviors, and the accuracy of complementary analytical models. Our review emphasizes the need for multi-scale approaches that incorporate ecological, climatic, and anthropogenic factors into habitat modeling to improve conservation strategies.

A key insight from this study is the discrepancy between technological advancements and their accessibility in conservation programs. While high-tech methodologies such as automated wind turbine curtailment, AI-driven habitat monitoring, and genetic analysis have yielded significant conservation benefits, their application remains unevenly distributed, particularly in regions with limited funding and infrastructure. Future conservation efforts must prioritize the development of cost-effective and scalable technologies that can be readily implemented in diverse ecological settings.

Furthermore, our analysis of reintroduction programs reveals that population viability strongly depends on demographic variables often overlooked in modeling, such as the age of first breeding and density-dependent factors. The omission of these variables can lead to inaccurate predictions of population stability, potentially undermining conservation efforts. Addressing these gaps through improved simulation models and long-term monitoring programs is essential for ensuring the success of reintroduction initiatives.

Integrating innovative technologies has transformed raptor research, offering unprecedented insights into species ecology and threats. However, the effectiveness of these approaches hinges on methodological standardization, cross-disciplinary collaboration, and equitable access to conservation tools. Moving forward, we advocate for a holistic approach combining cutting-edge technology with traditional ecological knowledge, ensuring that conservation strategies remain scientifically robust and practical for on-the-ground implementation. The future of raptor conservation depends on technological innovation and the commitment to fostering a globally coordinated effort that prioritizes data sharing, adaptive management, and community engagement.

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AUTHORSHIP CONTRIBUTION

Conceptualization: Gonzalo Espinosa.
Data curation: Francisco Naranjo.
Formal analysis: Julio Guerra.
Research: Gonzalo Espinosa.
Methodology: Gonzalo Espinosa, Julio Guerra.
Project management: Luis Mosquera.
Resources: Francisco Naranjo.
Software: Francisco Naranjo.
Supervision: Gonzalo Espinosa.
Validation: Julio Guerra.
Display: Luis Mosquera.
Drafting - original draft: Gonzalo Espinosa.
Writing - proofreading and editing: Julio Guerra.

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