Status and conservation assessment of southern marginal populations of the Golden Eagle *Aquila chrysaetos* under IUCN criteria

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Abstract

The Golden Eagle (*Aquila chrysaetos*) is one of the most widely distributed raptors worldwide and is currently classified as Least Concern at the global scale. However, global assessments may obscure pronounced regional asymmetries in population status and extinction risk, particularly at the geographical margins of a species' range. At the southern edge of its distribution, encompassing the Sahara, the Sahel, the Arabian Peninsula and the Afro-alpine systems of Ethiopia, Golden Eagle populations persist under extreme ecological conditions characterised by hyper-aridity, strong climatic variability and severe spatial fragmentation. Here we review the current status of southern marginal subpopulations of the Golden Eagle, provide updated information on their geographical distribution and confirmed breeding areas, and conduct a qualitative regional assessment of their conservation status under the IUCN Red List criteria. Information was synthesised from a systematic literature review, citizen-science platforms, expert knowledge and targeted field surveys conducted between 1993 and 2026. Confirmed breeding is mainly to a small number of isolated mountain massifs separated by distances that largely exceed documented effective dispersal ranges, with no evidence of regular demographic connectivity. Several regions hold recurrent records of the species but lack recent confirmation of reproduction. Our regional assessment indicates that southern marginal populations consistently meet thresholds associated with elevated extinction risk, including severe fragmentation, very small population sizes and continuing decline. Recent empirical evidence from Oman demonstrates a climate-driven collapse of reproduction beyond a narrow thermal threshold, resulting in functional extinction despite intermittent persistence of adult individuals. This provides a mechanistic framework for interpreting declines across other arid-zone populations. We conclude that the global Least Concern status of the Golden Eagle masks situations of high extinction risk at regional scales and that effective global conservation of the species requires explicit recognition and protection of its southern marginal populations.

Keywords: Aquila chrysaetos; marginal populations; rear-edge populations; Africa; Arabian Peninsula; Sahara; Sahel; IUCN Red List; conservation assessment; range fragmentation.

1. Introduction

Large apex raptors are often considered conservation successes when assessed at broad spatial scales, particularly species with extensive distributions and apparently stable population trends. The Golden Eagle (*Aquila chrysaetos*), one of the most widely distributed avian predators in the Holarctic, exemplifies this perception. It is currently classified as Least Concern, with an estimated global population of 51,442–87,033 breeding pairs (Ellis *et al*., 2024). The species occupies a wide range across North America, Eurasia and northern Africa, extending into isolated areas beyond its core Palearctic distribution, and uses diverse habitats including boreal forests, mountain systems, temperate regions and arid environments (Watson, 2010; Ellis *et al*., 2024).

Marginal populations, occurring at the geographical or ecological limits of a species' range, often experience environmental conditions that differ markedly from those in core areas. As a result, they may exhibit distinct demographic, behavioural and genetic characteristics. These populations can contribute disproportionately to evolutionary processes and long-term persistence by harbouring locally adapted traits and adaptive potential under environmental change. Their loss may therefore represent not only range contraction but also erosion of ecological and evolutionary diversity (Lesica & Allendorf, 1995; Channell, 2004).

Despite favourable global assessments, strong regional asymmetries in population status, connectivity and extinction risk may occur, particularly at range margins. At the southern edge of its distribution, the Golden Eagle persists under extreme conditions characterised by hyper-aridity, high climatic variability and pronounced habitat fragmentation (Clouet & Goar, 2006; Clouet & Barrau, 2015, 2017; Ellis *et al*., 2024; Bautista *et al*., 2026a). Suitable breeding habitat is largely restricted to isolated mountain massifs within extensive desert or heavily modified landscapes, resulting in low densities, small population sizes and prolonged demographic isolation.

Ecological and demographic processes in these peripheral systems may differ substantially from those in more continuous populations (Channell, 2004). In long-lived raptors, adult survival may remain relatively high despite environmental deterioration, whereas reproduction is more sensitive to climatic conditions, prey availability and habitat quality (Bautista *et al*., 2026a). This mismatch can generate a lag between environmental change and population disappearance, consistent with extinction debt (Tilman *et al*., 1994; Kuussaari *et al*., 2009). Populations may thus persist as apparently occupied systems while being functionally extinct due to lack of recruitment and progressive ageing.

Recent evidence suggests that some southern marginal populations of the Golden Eagle may already have crossed critical ecological thresholds. In the hyper-arid central desert of Oman, long-term analyses combining climatic data, repeated surveys of historical territories and demographic observations identified a climate-driven mechanism of collapse. Reproductive activity declined sharply once a narrow thermal threshold was exceeded, leading to functional extinction despite intermittent adult persistence (Bautista *et al*., 2026a). This decoupling between adult presence and reproduction provides a mechanistic example of climate-driven functional extinction and illustrates how extinction-debt dynamics may operate in arid environments. It also indicates that local extirpation may remain undetected when assessments rely primarily on adult occupancy.

In this context, a focused assessment of southern marginal populations is required. The aims of this study are to: (1) review the status of Golden Eagle subpopulations at the southern edge of the range; (2) update their distribution and confirmed breeding areas; and (3) provide a qualitative regional assessment of conservation status in Africa and the Arabian Peninsula under IUCN Red List criteria. This synthesis is intended to inform conservation prioritisation and regional Red List processes, and to highlight the limitations of global assessments for marginal, fragmented populations.

2. Material and Methods

2.1. Study area

This study focuses on the southern boundary of the Golden Eagle's global range across Africa and the Arabian Peninsula, encompassing the Sahara, the Sahel, the Arabian Peninsula, and the Afro-alpine systems of Ethiopia, located approximately between 6° and 24° N latitude (Fig. 1). Across most of this area, environmental conditions are dominated by arid and hyper-arid climates, where suitable habitat for the Golden Eagle is largely restricted to isolated mountain massifs embedded within extensive desert matrices or heavily transformed landscapes. These massifs typically provide the only combination of nesting substrates, prey availability and thermal refuges necessary for persistence in otherwise inhospitable surroundings.

An important exception is represented by the Bale Mountains in Ethiopia, where high elevations generate cold Afro-alpine climatic conditions that contrast sharply with the surrounding tropical and anthropogenically transformed lowlands. Despite this climatic contrast, the Ethiopian population is similarly isolated, occupying a very restricted area at high altitude and separated by thousands of kilometres from the nearest confirmed breeding populations.

Climatic conditions across most of the study area, with the exception of the Afroalpine habitats of the Bale Mountains, are characterised by low and highly variable precipitation, strong interannual variability, and frequent droughts. Temperature extremes are particularly pronounced in the Sahara, the Sahel and the Arabian Peninsula, where mean annual temperatures have increased substantially over recent decades (Foley *et al*., 2003; IPCC, 2023; Malik *et al*., 2024). Human pressures, although spatially heterogeneous, include habitat degradation, direct persecution, poisoning, infrastructure development, expansion of transport and energy networks, and increasing disturbance even in remote areas. In addition, access to several parts of the study area is constrained by long-standing social instability, armed conflict and security issues, which have inevitably limited the extent of field surveys and systematic monitoring. Together, these factors result in extremely fragmented, poorly connected and often poorly documented populations at the southern edge of the species' range.

2.2. Literature review

We conducted a systematic review of the available literature on the Golden Eagle in Africa and the Arabian Peninsula. Searches were performed in major scientific databases, including Web of Science (ISI), Scopus and Google Scholar, using structured Boolean queries combining species, geographic and thematic terms. The core search string included the following terms: ("Golden eagle" OR *Aquila chrysaetos*) AND (Africa OR Sahara OR Sahel OR "Arabian Peninsula" OR Arabia OR Ethiopia) AND (distribution OR breeding OR reproduction OR status OR population OR conservation). In Web of Science and Scopus, additional exclusion terms (e.g. NOT Europe, NOT "North America") were applied when necessary to reduce irrelevant results.

The search encompassed peer-reviewed journal articles, books, book chapters, technical reports and unpublished or grey literature when relevant. Reference lists of key publications were screened to identify additional sources not captured by the initial database searches. Only records providing information on species occurrence, breeding evidence, population status, trends or conservation threats within the study area were retained. Publications referring exclusively to migratory or vagrant individuals without relevance to resident or potentially breeding populations were excluded.

2.3. Citizen science data and observational records

To complement published information, we compiled occurrence records from citizen-science platforms widely used in ornithology, primarily eBird and iNaturalist. All available records of *Aquila chrysaetos* from Africa and the Arabian Peninsula were screened individually. Records were checked for spatial accuracy, duplication and potential misidentification, particularly with other large eagles occurring in arid environments. Only records supported by photographic evidence were retained.

Citizen-science data were used exclusively to confirm species presence and to identify areas of confirmed or potential occurrence, including regions where the species had not been documented through recent field surveys. These data were not used to estimate population size, density or trends, given the opportunistic nature of observations and the strong spatial bias in observer effort across the study area.

2.4. Expert knowledge and unpublished information

Given the scarcity of systematic monitoring programmes in many parts of the study area, we compiled unpublished information through direct consultation with experts working on raptors and other taxa in Africa and the Arabian Peninsula. This included ornithologists, conservation practitioners and researchers with extensive field experience in remote desert and mountain environments, affiliated with international conservation organisations as well as governmental and local institutions.

Expert input provided additional insights on recent breeding attempts, population persistence, local threats, historical records and areas where the species may still occur but remains poorly documented. Information obtained through personal communications was cross-checked whenever possible against independent observations or photographic evidence and is cited accordingly in the text.

2.5. Field surveys and expeditions

Targeted field surveys and expeditions were conducted in several parts of the study area between 1993 and 2026 (Table 1), focusing on mountainous regions with historical records or potential suitability for Golden Eagles. These surveys aimed to verify species presence, assess breeding activity where possible and gather contextual information on habitat conditions, prey availability and threats.

Survey methods varied according to local conditions, accessibility and security constraints, but generally included systematic searches of suitable nesting cliffs, inspection of historical nesting territories, opportunistic observations during transects and vantage-point surveys. In some regions, repeated visits over multiple years allowed assessment of breeding persistence or abandonment. Survey effort, locations and dates are summarised in Table 1 and were provided by the respective co-authors with direct field involvement.

2.6. Conservation assessment under IUCN criteria

The conservation status of southern marginal populations of the Golden Eagle was evaluated in relation to the IUCN Red List Categories and Criteria at a regional scale, following the Guidelines for Application of IUCN Red List Criteria at Regional and National Levels (IUCN Standards and Petitions Committee, 2024). This assessment synthesised all available information on population size, demographic trends, extent of occurrence, area of occupancy, degree of fragmentation, population isolation, and documented threats.

Each population was evaluated qualitatively against the thresholds defined under Criteria A–D. Criterion A was considered in relation to inferred and observed evidence of population reduction, including historical contraction of breeding territories and documented declines in reproductive output. Criterion B was assessed using spatial parameters (extent of occurrence and area of occupancy), together with the degree of fragmentation and isolation of breeding nuclei. Criteria C and D were evaluated in relation to estimates of population size and the number of mature individuals, as well as field-based evidence of extremely small and/or restricted populations. Criteria A–D were applied at the regional population level following IUCN regional guidelines, with particular attention to geographic and demographic isolation from the global population. Criterion E was not applied due to the absence of robust demographic parameters required for quantitative population viability analysis.

In accordance with IUCN regional guidelines, the potential for demographic or genetic rescue from neighbouring populations was also considered qualitatively, although no quantitative estimates of dispersal or connectivity were available.

This assessment does not assign formal IUCN Red List categories. Instead, it evaluates whether these marginal populations approach thresholds associated with elevated extinction risk, with the aim of contextualising their conservation importance relative to the global status of the species.

3. Results

3.1. Overview of data availability and sources

The systematic literature review yielded a total of 40 publications relevant to the occurrence, breeding status, population trends or conservation of the Golden Eagle within the southern marginal range considered in this study. Because individual publications frequently referred to more than one region or reported multiple types of information, categories were not mutually exclusive. Of the publications analysed, 21 referred to Sahelo-Saharan populations, nine to Ethiopian populations and ten to populations in the Arabian Peninsula. With respect to the type of information provided, 19 publications reported evidence of confirmed reproduction, 38 reported presence records and 15 addressed population status, trends or conservation threats.

The compiled information revealed a highly uneven spatial and temporal coverage across the southern marginal range of the species. Published data were concentrated in a limited number of regions that have historically received more ornithological attention or where access has been possible over extended periods, whereas vast areas lacked recent or systematic information. Temporal coverage also varied widely, with some regions documented by long-term observations spanning several decades and others represented only by isolated historical records.

Citizen-science platforms contributed a total of 24 confirmed photographic records. Of these, 15 were obtained from eBird, including 13 records from the Arabian Peninsula and two from Sahelo-Saharan regions, while nine records were obtained from iNaturalist, including seven from Sahelo-Saharan regions, one from the Arabian Peninsula and one from Ethiopia. These records provided valuable confirmation of presence in regions where recent field surveys are limited or absent, but were spatially biased towards areas with higher observer activity and accessibility.

Expert consultations yielded an additional 11 reliable observations, including three from Sahelo-Saharan regions and eight from the Arabian Peninsula. Most of these records were supported by photographic documentation or detailed field notes and provided important contextual information on recent occurrence, breeding attempts, habitat use and threats in poorly documented regions. Taken together, the combination of published sources, citizen-science data, expert knowledge and targeted field surveys allowed a comprehensive synthesis of the current status of southern marginal populations, despite the inherent limitations imposed by uneven data availability.

3.2. Distribution and confirmed breeding areas

Across Africa and the Arabian Peninsula, the southern marginal distribution of the Golden Eagle is extremely fragmented and discontinuous. Confirmed breeding is restricted to a small number of isolated mountain massifs embedded within extensive arid or hyper-arid landscapes. These breeding nuclei are separated by distances that often exceed several hundred kilometres and, in many cases, approach or surpass one thousand kilometres, with no evidence of regular demographic connectivity. Several regions hold recurrent records of the species, sometimes over extended periods, but lack recent confirmation of breeding activity.

The following sections provide a regional overview of the current distribution, breeding status and conservation context of the Golden Eagle across the main subregions of its southern marginal range.

3.2.1. Sahara and Sahel

In the Sahara and the Sahel, the breeding records Golden Eagles included in this study are concentrated in a very limited number of mountain massifs located approximately south of the 24° N parallel. Confirmed breeding has been documented in the Moroccan Atlantic Sahara, the Adrar region of Mauritania, l'Adrar Tirharhar and the Adrar des Ifoghas in Mali, the Ahaggar (Hoggar) massif in Algeria and the Aïr Mountains in Niger (Goar & Rutkowsky, 2000; Clouet & Goar, 2004, 2006; Chevalier & Bergier, 2011; Garrido & Bautista, 2024; Qninba *et al*., 2024; Bautista *et al*., 2025; Bautista *et al*., 2026b; Authors' observations) (Table 1). In contrast, in other steppe areas of the Ennedi and Kanem regions of Chad, only sporadic sightings have been recorded, with no recent confirmation of breeding (Wacher & Newby, 2010; T. Wacher, com. Pers.).

Breeding nuclei in this region are widely separated, with mean distances of approximately 600 km (range: 300–970 km) between confirmed breeding massifs. When massifs with recurrent but unconfirmed records are included, inter-site distances increase to approximately 985 km (range: 770–1,200 km). Such distances far exceed those documented for effective dispersal and recruitment in Golden Eagles and strongly suggest demographic isolation between breeding nuclei.

Available information indicates exceptionally low population densities across the region, with each massif typically supporting no more than one or a few breeding pairs. Historical accounts suggest that some massifs may have supported larger numbers in the past, but several breeding territories documented in the late twentieth century have not been reoccupied in recent decades (Clouet & Goar, 2006; Garrido & Bautista, 2024; Bautista *et al*., 2025; Bautista *et al*., 2026b). Although adult individuals continue to be observed sporadically in some regions, the absence of confirmed breeding over extended periods suggests that several local populations may already be functionally extinct or in the final stages of demographic collapse.

3.2.2. Arabian Peninsula

Available data indicate a marked contraction and fragmentation of the breeding distribution of the Golden Eagle across the Arabian Peninsula. In Oman, confirmed breeding was first documented in 1980–1981, when two active nests were located in the central desert (Gallagher & Brown, 1982). During the 1980s, up to seven breeding territories were identified in this area, with an estimated maximum of approximately 12 breeding pairs. From the early 1990s onwards, reproductive activity declined sharply, with only sporadic breeding attempts recorded over the following two decades (Green & Harrison, 2014, 2021).

Recent analyses integrating long-term climatic data (1980–2026), repeated surveys of at least 21 historical breeding territories, and independent demographic observations provide robust empirical support for a scenario of functional extinction in the central desert population of Oman (Green & Harrison, 2014, 2021; Bautista *et al*., 2026a). Reproductive activity declined non-linearly and collapsed to near zero once mean annual temperature exceeded a narrow threshold of approximately 28.3–28.6 °C (Bautista *et al*., 2026a). Notably, adult presence persisted intermittently following the cessation of reproduction, indicating a marked decoupling between occupancy and demographic viability.

Independent long-term observational data further document a progressive erosion of population age structure. Juveniles and immatures declined sharply from the late 1990s onwards and disappeared entirely more than a decade before the last adult records, resulting in a senescent, non-recruiting population dominated by isolated adults. Concurrently, the use of key functional habitats, such as desert oases that historically acted as hydric and thermal refugia, declined markedly, indicating a loss of landscape functionality. Taken together, these convergent lines of evidence indicate that the Golden Eagle population in the central desert of Oman is functionally extinct in terms of reproductive failure, rather than experiencing short-term demographic fluctuation. On the contrary, repeated documented observations (eBird, 2026; C. Gutiérrez, pers. comm.) outside this area, in other desert regions influenced by the western monsoon in Dhofar, support the possibility that some breeding pairs may persist or have undergone a climate-driven shift toward these climatic refugia beyond the hyper-arid central desert.

In Saudi Arabia, the first record of breeding dates back to 1948, when a chick and an egg were collected near Jeddah (Meinertzhagen, 1949). Historical and recent observations of Golden Eagles in interior desert regions such as Uruq Bani Ma'arid Protected Area, Rub' al-Khali and Ibex Reserved Area (Jennings, 2010; Wacher *et al*., 2019; M. Prommer, pers. comm.), mountain systems of Jibal al-Sarawat (eBird, 2026), and rocky deserts of Al-Ula Governorate (L. Patkó and J. Sousa, pers. comm.), indicate continued presence of the species, although no breeding has been confirmed. Additionally, telemetry data from individuals marked in Israel indicate regular use of northern Saudi Arabia during natal dispersal, with documented mortality events associated with electrocution and poisoning (A. Myrose and O. Hatzofe, pers. comm.).

In the United Arab Emirates, the species has been recorded consistently for more than three decades, with sporadic breeding events in remote areas of the southwestern region, such as Al Beda'a and Qasr Al Sarab Protected Areas (Pedersen *et al*., 2023; J. Judas, pers. comm.). However, these areas are increasingly affected by habitat degradation linked to infrastructure development, oil exploration, and historical instances of illegal hunting (J. Judas, pers. comm.). In Yemen, possible breeding of Golden Eagles has historically been recorded in the arid mountain ranges of the north and southwest (Thiollay & Duhaultois, 1976), but recent data are lacking due to the prolonged conflict and absence of systematic studies. In the remaining countries of the Arabian Peninsula, such as Bahrain, Kuwait and Qatar, the species has only been recorded sporadically, mainly as wandering juveniles, with no confirmed evidence of breeding.

3.2.3. Ethiopia

The Ethiopian population represents the most extreme case of isolation within the southern marginal range of the Golden Eagle. The species is restricted to the Afro-alpine ecosystems of the Bale Mountains, occupying an area estimated at approximately 200 km² (Clouet & Barrau, 1993; Clouet *et al.*, 1999; Clouet & Barrau, 2015; Wentworth, 2018, 2019; Bautista *et al.*, 2024). This population is separated by more than 1,500 km from the nearest confirmed breeding populations in the Sahara and the Arabian Peninsula.

Recent surveys conducted between 2018 and 2019 confirmed the presence of only seven individuals occupying four territories. The total number of mature individuals is estimated at fewer than 12–15, placing this population well below commonly accepted thresholds for demographic viability (Wentworth, 2018, 2019; Bautista *et al*., 2024). Field observations indicate low reproductive output and high vulnerability to environmental stochasticity, grazing pressure and habitat degradation within the Afro-alpine zone (Wentworth, 2018, 2019; Bautista *et al*., 2024; authors, personal data).

3.2.4. Mountain systems with potential but unconfirmed presence

Beyond areas with confirmed breeding, several mountainous systems across North and East Africa are considered to provide suitable habitat for the presence and potential reproduction of Golden Eagles. These include the Tagant Plateau in Mauritania, the Bir Moghrein region and the Amguel Plateau in Algeria, the Tadrart and Acacus ranges in Libya, the Djado Plateau and Termit Massif in Niger, Tibesti and Ennedi in Chad, Gilf Kebir and the massifs of Egypt's Eastern Desert, the Meidob Massif in northern Sudan, as well as the Eritrean and Djiboutian massifs. Nevertheless, many of these regions are situated in areas affected by ongoing political instability or severe logistical and security constraints, which currently limit the feasibility of conducting systematic field surveys and comprehensive ecological assessments.

3.3. Regional conservation assessment under IUCN criteria

Application of the IUCN Red List criteria at a regional scale indicates that southern marginal populations of the Golden Eagle (*Aquila chrysaetos*) are consistently exposed to high levels of extinction risk, although the specific drivers and criteria met vary among regions (Table 2).

In the Sahara–Sahel region, populations are highly fragmented and occur in a very limited number of isolated mountain massifs, with extremely large inter-nuclear distances and no evidence of demographic connectivity or recolonisation. This pattern results in the application of Criteria B1ab(i,ii,iii,v) and B2ab(i,ii,iii,v), together with indications of very small population size under Criterion D1, supporting a qualitative assessment of elevated risk, interpreted here as Endangered (EN) at a regional scale.

On the Arabian Peninsula, the evidence indicates a severe and ongoing decline in breeding territories, including the disappearance of most historical sites and the functional collapse of key populations such as those in Oman. These trends, combined with strong isolation, persistent threats, and lack of demographic rescue, satisfy multiple criteria including A2 and A4 (population reduction), B1ab(v) (declining habitat/number of mature individuals), C1 and C2(a)(i) (continuing decline and small subpopulation structure), and D1 (very small population). Collectively, these factors support a regional classification of Critically Endangered (CR).

In the Ethiopian highlands (Bale Mountains), the population is extremely restricted in range (AOO ≈ 200 km^2), composed of fewer than 15 mature individuals, and completely isolated from other populations. This configuration meets Criteria B2ab(i,ii,iii,v), C2(a)(i), and D, reflecting both severe geographic restriction and extreme demographic vulnerability to stochastic events. As a result, this population is also assessed as Critically Endangered (CR).

No quantitative population viability analyses were available to evaluate Criterion E in any of the assessed regions.

4. Discussion

4.1. Extreme fragmentation and demographic isolation at the southern edge of the range

The results presented in this study demonstrate that Golden Eagle populations at the southern margin of the species' global distribution are characterised by extreme spatial fragmentation and prolonged demographic isolation. In Africa and the Arabian Peninsula, confirmed breeding is restricted to a small number of isolated mountain ranges and desert areas, separated by distances far exceeding those documented for the species' effective dispersal and recruitment (Watson, 2010; Fielding *et al*., 2024). This spatial configuration strongly suggests that these populations function as largely independent demographic units, with little or no opportunity for regular demographic rescue through immigration.

Such levels of isolation contrast sharply with the situation in the core Palearctic range, where populations are generally more continuous and connected, and where dispersal among breeding areas contributes to regional persistence (Ellis *et al.*, 2024). Historically, marginal southern populations were likely never abundant due to the inherent constraints of these harsh environments and may have persisted in part through episodic immigration from larger northern populations. However, increasing climatic pressures, such as evident global warming, combined with intensifying human pressures, appear to have disrupted these connections in recent decades (Ellis *et al*., 2024; Bautista *et al*., 2026a), resulting in populations that now operate independently within the species' global distribution range.

As a consequence, population persistence at the southern edge is likely governed primarily by local demographic processes and environmental stochasticity, rather than by regional-scale dynamics. Under such conditions, the loss of a single breeding nucleus may represent an irreversible step towards regional extirpation. This reinforces the need to avoid extrapolating global or continental population trends to marginal populations, where extinction risk may be orders of magnitude higher despite apparent global stability.

4.2. Dispersal limitations and functional barriers in arid landscapes

Although the golden eagle is a species with high mobility and the capacity to travel long distances, its effective dispersal depends not only on its flight ability but also on landscape structure, habitat suitability, and behavioral constraints. The species exhibits pronounced natal philopatry, with individuals typically recruiting relatively close to their natal areas (Soutullo *et al*., 2006, 2013; Urios *et al*., 2007; Watson, 2010; Weston, 2014). Recent telemetry studies further demonstrate that landscape configuration can severely limit effective dispersal, even in large soaring raptors (Fielding *et al*., 2024).

In arid and hyper-arid environments, the extensive desert plains separating mountain ranges may function as strong ecological barriers. Low prey availability, scarcity of water and thermal refuges, and increasingly extreme climatic conditions reduce the likelihood that dispersing individuals can survive long enough to locate and occupy suitable breeding habitat. Physical distances between breeding nuclei in the Sahara, the Sahel, and the Arabian Peninsula frequently exceed several hundred kilometers, and in many cases approach or surpass one thousand kilometers. Under such conditions, even rare long-distance movements are unlikely to result in meaningful demographic connectivity.

Recent studies on *Aquila fasciata* show that juvenile dispersal is strongly influenced by natal habitat, and that natural barriers such as extensive arid zones and water bodies limit both the direction and success of dispersal. Although some individuals originating from desert habitats can undertake extraordinary movements across extensive arid areas to reach the Sahel or southern Arabia, the majority experience high mortality rates and low establishment success. This confirms that deserts act as functional barriers that constrain effective dispersal and demographic connectivity. Moreover, individuals tend to settle in areas with climatic conditions similar to those of their natal habitat, supporting the natal habitat preference induction (NHPI) hypothesis (Mayrose *et al*., 2025).

Consequently, the likelihood that the loss of a local breeding nucleus is compensated through natural recolonization is low or nearly negligible, substantially increasing the probability of permanent regional extirpations. This pattern has been documented in other raptor species inhabiting fragmented desert landscapes and appears to be a defining characteristic of golden eagle populations at the southern limit of their distribution (Clouet & Goar, 2004; Clouet *et al*., 2006; Mayrose *et al*., 2025).

4.3. Climatic dependence and vulnerability in arid environments

A defining characteristic of southern marginal populations of the Golden Eagle is their strong dependence on climatic conditions. In arid and semi-arid environments, reproductive success has traditionally been linked to interannual variation in precipitation, mediated through its effects on primary productivity and prey availability (Bahat, 1989; Bahat & Mendelssohn, 1996; Clouet & Goar, 2004; Clouet *et al.*, 2006). Prolonged droughts can therefore result in consecutive years of reproductive failure, with disproportionate demographic consequences in small and isolated populations.

Recent evidence from Oman indicates that temperature itself may constitute a hard physiological constraint in hyper-arid environments. In this system, reproductive collapse occurred once a narrow thermal threshold was exceeded, and interannual variability in precipitation did not rescue reproduction beyond this limit (Bautista *et al.*, 2026a). This pattern suggests that gradual warming can generate abrupt, non-linear demographic responses once critical thresholds are crossed. Experimental and field studies on large desert birds support this interpretation, showing that extreme temperatures can impair gametogenesis, embryo viability and incubation behaviour (Schou *et al.*, 2021; Pattinson *et al.*, 2022).

In long-lived species such as the Golden Eagle, adult survival may remain relatively high even when reproductive conditions deteriorate, leading to a temporal decoupling between adult presence and population viability. Repeated years of reproductive failure rapidly erode recruitment and age structure, ultimately resulting in senescent populations with no demographic replacement (Bautista *et al*., 2026a). Under current and projected climate change scenarios, continued warming across the Sahara, Sahel and Arabian Peninsula is therefore likely to amplify extinction risk in southern marginal populations well before adult disappearance becomes evident.

4.4. Conservation relevance of marginal and rear-edge populations

From a conservation perspective, the southern marginal populations of the Golden Eagle exemplify the importance of rear-edge populations within wide-ranging species. Peripheral populations have historically been regarded as demographically unstable, genetically impoverished and of limited conservation value. However, both theoretical and empirical work has demonstrated that rear-edge populations can persist over long evolutionary timescales, harbour unique genetic variation and experience selective regimes that differ markedly from those operating in the centre of the species' range (Lesica & Allendorf, 1995; Hampe & Petit, 2005).

Modern conservation frameworks increasingly emphasise the identification of Evolutionarily Significant Units (ESUs) and Management Units (MUs) as a basis for prioritisation and decision-making (IUCN, 2022). These units are typically defined by a combination of genetic differentiation, long-term demographic independence, ecological distinctiveness and exposure to specific threats. In the case of the Golden Eagle, available phylogeographic evidence indicates prolonged isolation of Saharan populations from the core Palearctic range (Wink *et al.*, 2004; Clouet *et al.*, 2006). Although genetic data remain limited, the persistence of isolation over extended timescales, together with extreme ecological conditions and documented demographic independence, supports the recognition of these populations as independent conservation units.

The exposure of southern marginal populations to extreme environmental conditions—including both highly arid and unpredictable desert landscapes and isolated Afroalpine mountain systems—further enhances their potential evolutionary significance. Long-term persistence under such conditions implies adaptation to ecological contexts that are rare or absent within the core range of the species. As a result, these populations likely contribute disproportionately to the ecological breadth and adaptive potential of the Golden Eagle at a global scale.

4.5. Implications of the regional IUCN assessment

The regional application of IUCN Red List criteria reveals a consistent pattern of elevated extinction risk across the southern marginal populations of the Golden Eagle, with marked spatial variation in severity. While the results section (Table 2) identifies clear differences in assigned categories among regions, these classifications reflect a shared underlying syndrome of fragmentation, isolation, and demographic decline at the range margin.

In the Arabian Peninsula and Ethiopia, the Critically Endangered status reflects not only extremely small population sizes and severe range restriction, but also advanced stages of demographic collapse. In these regions, the convergence of ongoing declines, isolation from source populations, and absence of detectable demographic rescue suggests that local populations may already be operating under extinction-debt conditions. This is particularly evident in the Omani population, where functional extinction likely preceded the disappearance of remaining individuals, highlighting a temporal lag between demographic collapse and apparent occupancy loss.

By contrast, the Sahara–Sahel populations, assessed as Endangered in the results due to strong fragmentation and isolation, appear to represent an earlier stage along the same continuum of risk. Although demographic connectivity appears to be absent and dispersal distances between population nuclei are exceptionally large, some subpopulations may persist above the most extreme thresholds observed in the Arabian Peninsula and Ethiopia. This suggests that, while extinction risk is high, the demographic trajectory in this region may be less advanced, although still consistent with long-term decline under continued isolation.

Across all regions, the consistency of Criteria B-based patterns (geographic fragmentation and restricted range) indicates that spatial structure is a fundamental driver of vulnerability at the southern range margin. However, the application of Criteria C and D in the most affected regions (Arabian Peninsula and Ethiopia) highlights that small population size and extreme demographic isolation are critical amplifiers of extinction risk beyond spatial restriction alone.

From a methodological perspective, these findings demonstrate the limitations of occupancy-based or presence–absence assessments when applied to long-lived raptors with delayed demographic responses. The persistence of adults in some regions, particularly in Oman, may mask underlying reproductive failure and demographic collapse, leading to systematic underestimation of extinction risk if functional parameters are not considered. This reinforces the importance of incorporating reproductive performance, age structure, and functional habitat use into regional assessments under the IUCN framework.

Overall, the results and their interpretation jointly indicate that southern marginal populations of the Golden Eagle are not uniformly declining, but rather represent different stages along a gradient of fragmentation-driven extinction risk, with clear implications for monitoring and conservation prioritisation under ongoing environmental change.

5. Conclusions

Southern marginal populations of the Golden Eagle in the Sahara, the Sahel, the Arabian Peninsula, and Ethiopia represent a clear example of population persistence at the ecological and geographical limits of a wide-ranging raptor. Rather than constituting marginal extensions of a continuous Palearctic distribution, these populations function as largely isolated demographic units exposed to extreme climatic conditions, severe spatial fragmentation, and region-specific anthropogenic pressures that substantially increase extinction risk.

The evidence synthesized in this study indicates that the global classification of the Golden Eagle as Least Concern masks important regional conservation concerns. In these desert, hyper-arid, and Afroalpine systems, the loss of only one or a few breeding territories may lead to rapid regional extirpation, with no realistic prospects for natural recolonization due to the apparent absence of demographic connectivity.

From a biogeographical and evolutionary perspective, the disappearance of these peripheral populations would result in a substantial reduction of the species' ecological and adaptive diversity. These populations may also represent a potential genetic reservoir of adaptation to extreme environmental conditions, as they persist under climatic and ecological regimes that are markedly different from those of core populations.

The regional assessment based on IUCN Red List criteria indicates marked spatial heterogeneity in extinction risk across the southern range margin, with populations ranging from Endangered (Sahara–Sahel) to Critically Endangered (Arabian Peninsula and Ethiopia). This pattern highlights a continuous gradient of risk driven by increasing fragmentation, isolation, and demographic limitation towards the southern extremes of the species' distribution.

Overall, effective conservation of the Golden Eagle at the global scale requires the explicit recognition and protection of these peripheral populations, whose loss would lead to an irreversible contraction of the species' distribution, a significant reduction in its biogeographical and ecological breadth, and the potential loss of a reservoir of adaptive genetic variation associated with survival in extreme environments.

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8. Conflicts of Interest

The authors declare none.

9. Data Availability Statement

Data supporting the results of this study are available from the corresponding author upon reasonable request, subject to relevant conservation, ethical and data-sharing constraints.

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Table 1. Summary of field surveys, observational records and compiled evidence for Golden Eagle (*Aquila chrysaetos*) populations across the southern margin of its range in Africa and the Arabian Peninsula between 1993 and 2026. Population nuclei are numbered according to their location in Figure 1, allowing direct spatial correspondence between mapped areas and tabulated records. For each site, geographic coordinates, elevation range, dominant habitat, survey period (including both fieldwork and historical records), and evidence of species presence and breeding status are provided. "Confirmed presence" refers to records supported by direct observation or documented evidence (including photographic records and expert validation). "Confirmed breeding" indicates verified reproduction (e.g. active nests, eaglets, or repeated breeding behaviour). Entries marked as "uncertain" correspond to areas with recurrent observations but lacking recent or conclusive evidence of breeding. Sources include published literature, citizen-science platforms, expert communications and authors' field observations.

Region / Country	**Geographic coordinates**	**Elevation (m a.s.l.)**	**Main habitat**	**Survey dates or records**	**Confirmed presence**	**Confirmed breeding**	**Source**
Atlantic Sahara, Morocco **(1)**	21°20′–23°44′ N, 14°14′–14°32′ W	200–480	Inland Saharan hamada and reg desert with gravel plains, low rocky plateaus, ephemeral wadis and sparse xerophytic shrubland	Nov 2023 – Apr 2026	Yes	Yes	Valverde, 1957; Quinba *et al*., 2024; iNaturalist, 2026; Bautista *et al*., 2026b; Authors' observations
Adrar region, Mauritania **(2)**	18°30′–20°60′ N, 09°34′–13°00′ W	260–700	Saharan rocky plateau (hamada) with escarpments, deep wadis, canyon systems and isolated gueltas	Oct 2003 – Jan 2025	Yes	Yes	Salewski *et al*., 2005; Isenmann *et al*., 2010; Clouet & Joachim, 2013; Santarém *et al*., 2018; Bautista *et al*., 2025; iNaturalist, 2026; Authors' observations
Tagant region, Mauritania **(12)**	17°17′–18°30′ N, 07°30′–09°34′ W	250–350	Arid Saharan landscape of rocky plateaus (hamada) interspersed with extensive aeolian sand deposits, including	Oct 2003	Yes	¿?	Salewski *et al*., 2005

Region / Country	Geographic coordinates	Elevation (m a.s.l.)	Main habitat	Survey dates or records	Confirmed presence	Confirmed breeding	Source
			dune fields surrounding rocky outcrops, with escarpments and intermittent wadis				
Ahaggar and Tassili Mountains, Algeria **(5)**	22°15′–24°50′ N, 6°30′–5°50′ E	800–1750	High Saharan volcanic massif with cliffs, rocky plateaus, steep escarpments and dry wadis (montane desert)	Dec 2001 – Oct 2025	Yes	Yes	Clouet & Goar, 2006; Clouet & Joachim, 2013; Z. Brahimi, pers. comm.; eBird, 2026; iNaturalist, 2026; Authors' observations
l'Adrar Tirharhar and the Adrar des Ifoghas, Mali **(3)**	19°25′–19°60′ N, 00°55′–01°15′ E	450–600	Granitic Saharan massif with rugged relief, rocky slopes, shallow valleys and seasonal gueltas	Feb 2003 – Mar 2007	Yes	Yes	Clouet & Goar, 2003, 2006; Clouet & Joachim, 2013; Authors' observations
Aïr, Niger **(4)**	17°35′–19°10′ N, 8°44′–8°40′ E	1300–1700	Montane Saharan desert with rocky massifs, inselbergs, dry wadis and sparse xeric woodland	Dec 2001 – Mar 2002	Yes	Yes	Goar & Rutkowsky, 2000; Clouet & Goar, 2004, 2006; Clouet & Joachim, 2013; Authors' observations
Red Sea Mountains, Egypt **(15)**	23°25′–27°14′ N, 33°20′–35°40′ E	400–1930	Arid coastal mountain range with steep escarpments, rocky valleys (wadis) and desert shrubland	Mar 2010 – Jun 2025	Yes	¿?	Clouet & Joachim, 2013; A. Camiña, pers. comm.; eBird, 2026; iNaturalist, 2026; Authors' observations
Kanem region, Chad **(13)**	15°01′ N, 15°18′ E	360	Sahelian semi-arid steppe with open shortgrass	Aug 2010	Yes	¿?	Wacher & Newby, 2010

Region / Country	Geographic coordinates	Elevation (m a.s.l.)	Main habitat	Survey dates or records	Confirmed presence	Confirmed breeding	Source
			plains, scattered shrubs and seasonal drainage lines				
Steppe plains SW of Ennedi Massif, Chad **(14)**	16°22′ N, 19°55′ E	390	Open Sahelian steppe with flat plains, sparse grass cover, low shrubs and ephemeral watercourses	Oct 2025	Yes	¿?	T. Wacher, M. Ali, O. Annadif, pers. comm.
Bale Mountains, Ethiopia **(6)**	6°41′–7°01′ N, 39°43′–39°50′ E	3200–4300	Afro-alpine grasslands and heathlands with high-altitude plateaus, cliffs and montane moorlands	Aug 1993 – Feb 2019	Yes	Yes	Clouet & Barrau, 1993, 2015, 2017; Clouet *et al*., 1999; Bautista, 2017; Wentworth, 2018, 2019; Bautista *et al*., 2024; iNaturalist, 2026; Authors' observations
Central Desert, Oman **(11)**	17°28′–21°58′ N, 53°20′–57°28′ E	200–550	Hyper-arid desert characterised by extensive gravel plains, low rocky outcrops and plateaus, ephemeral wadis, and extremely sparse vegetation dominated by Acacia spp. and Ghaf (*Prosopis cineraria*) trees	1980 – 2026	Yes	Yes	Gallagher & Brown, 1982; Eriksen & Victor, 2013; Green & Harrison, 2014, 2021; eBird, 2026; Bautista *et al*., 2026a; Jens & Hanne Eriksen, personal records of species from Oman (1975–2020), pers. comm; Ali Al Rasbi, pers. comm.; Authors' observations
Rub' al Khali, United Arab Emirates **(9)**	22°80′–23°60′ N, 54°18′–54°09′ E	120–160	Arid dune desert with extensive sand seas, interdune plains, sabkhas (saline flats) and oasis	1990 – 2023	Yes	Yes	Pedersen *et al*., 2023; pers. comm.; eBird, 2026; iNaturalist, 2026; J. Judas, T. Pedersen, O. Campbell, pers.

Region / Country	Geographic coordinates	Elevation (m a.s.l.)	Main habitat	Survey dates or records	Confirmed presence	Confirmed breeding	Source
			pockets with date palm cultivation				comm.
Rub' al Khali, Saudi Arabia **(10, 18)**	19°12′–19°50′ N, 45°23′–53°13′ E	185–825	Vast continuous sand seas with extensive dune fields, interspersed with rocky outcrops and gravel plains, low escarpments, and occasional seasonal wadis, supporting very sparse xerophytic vegetation adapted to extreme aridity	1949 – 2019	Yes	Yes	Meinertzhagen, 1949; Wacher *et al.*, 2019
Tuwaiq Escarpment, Saudi Arabia **(17)**	23°25′ N–46°22′ E	770–1180	Limestone escarpment and plateau landscape with steep cliffs, dissected by wadis and adjacent rocky desert and gravel plains, supporting sparse xerophytic vegetation adapted to arid conditions	Dec 2025	Yes	¿?	M. Prommer, pers. comm.
Al-Ula region, Saudi Arabia **(16)**	25°51′–27°26′ N, 38°09′–37°32′ E	500–1450	Extensive sandstone formations, rock outcrops, canyons and cliffs, interspersed with sandy plains, wadis, and adjacent volcanic fields (harraat), supporting	2023	Yes	¿?	L. Patkó, J. Sousa, pers. comm.

Region / Country	Geographic coordinates	Elevation (m a.s.l.)	Main habitat	Survey dates or records	Confirmed presence	Confirmed breeding	Source
			sparse desert-adapted vegetation and localized oasis-associated flora				
Sarawat Mountains, Saudi Arabia **(7)**	21°41′ N–39°43′ E	240–560	High escarpments and rugged peaks, dissected by deep wadis and terraces, with gradients from arid rocky slopes to relatively moister highlands supporting sparse to patchy shrubland and montane vegetation influenced by seasonal monsoon conditions	1949	Yes	Yes	Meinertzhagen, 1949
Yemen **(8)**	17°11′ N, 43°58′ E	2000	South-west Arabian highlands with montane grasslands, rocky escarpments and remnant juniper	1976	Yes	Yes	Thiollay & Duhaultois, 1976

Table 2. Regional assessment of southern marginal populations of the Golden Eagle (*Aquila chrysaetos*) following IUCN Red List criteria (qualitative interpretation based on available evidence; not an official IUCN assessment; criteria interpreted following IUCN Red List Guidelines [IUCN Standards and Petitions Committee, 2024]).

Region	**Key evidence**	**Relevant IUCN criteria met**	**Regional Red List category (qualitative)**
Sahara–Sahel	Highly fragmented distribution; breeding restricted to a few isolated mountain massifs; very large distances between nuclei (hundreds of km); extremely low densities; no evidence of recolonisation or demographic connectivity	B1ab(i,ii,iii,v); B2ab(i,ii,iii,v); C2(a)(i); D1 (inferred/suspected based on available evidence)	Endangered (**EN**)
Arabian Peninsula	Severe decline in number of breeding territories; most historical breeding areas no longer confirmed; functional collapse in the most important population in Oman; persistent threats; absence of demographic rescue; extremely low densities and strong isolation	A2 (observed/estimated decline over 3 generations); A4 (past–future decline over 3 generations); B1ab(v); C1; C2(a)(i); D1	Critically Endangered (**CR**)
Ethiopia (Bale Mountains)	Extremely restricted range (AOO ≈ 200 km^2); population estimated <15 mature individuals; complete isolation; high vulnerability to stochastic processes; no evidence of connectivity	B2ab(i,ii,iii,v); C2(a)(i); D	Critically Endangered (**CR**)

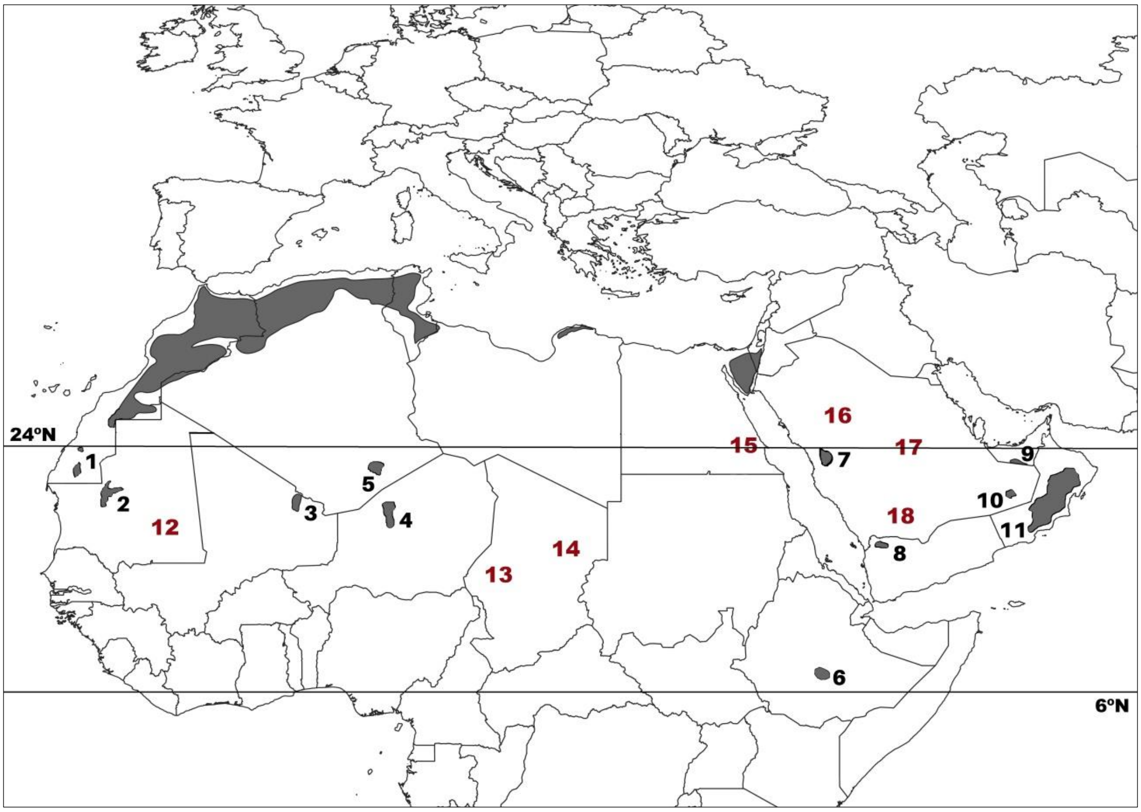

Figure 1. Southern marginal distribution of the Golden Eagle (*Aquila chrysaetos*) across Africa and the Arabian Peninsula (6°–24° N), illustrating a highly fragmented arrangement of isolated population nuclei, mostly associated with isolated mountain massifs. Shaded areas denote regions with confirmed occurrence and verified breeding, whereas red-numbered sites indicate localities with recorded presence but no evidence of reproduction. Numbered labels correspond to the population nuclei detailed in Table 1, enabling cross-referencing of geographic location, survey effort, and breeding status. The spatial pattern reflects strong geographic and climatic constraints, with extensive arid and hyperarid barriers and limited effective dispersal capacity resulting in pronounced isolation among nuclei, where inter-site distances exceed known dispersal ranges and support demographic separation into largely independent subpopulations.