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Global conservation status and population trends of the Sooty Falcon *(Falco concolor)*

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Abstract Monitoring bird populations is important for tracking trends and spotting declines early. Reliable population data helps guide conservation efforts and assess extinction risks. Gathering consistent data in remote or uneven terrains is challenging, especially for the Sooty Falcon *(Falco concolor)*, which was recently classified as Vulnerable due to various threats and a declining population trend. This study analyses the population trends of this small falcon based on breeding pairs over a 12-year period, using data from 10 countries within the species' range. A stochastic simulation, accounting for uncertainty through error classes, was performed using bootstrap methods to refine population projections. The global average change over three generations indicates a slight decrease of -5.45%, with confidence intervals ranging from -30% to +31%. Declines are observed in most countries, particularly across the Arabian Peninsula, where large islands and coastal areas have seen a 20–25% reduction. In contrast, desert regions have experienced a 20–30% increase, primarily due to expanded exploration, not necessarily to real population growth.

This comprehensive study highlights the need for expanded monitoring and coordinated efforts to address the ongoing population decline, with particular attention to vulnerable populations in diverse environmental contexts.

Keywords: breeding populations, species range, monitoring, stochastic simulation, decline

Összefoglalás A madárpopulációk monitorozása kulcsfontosságú a hosszú távú változások követéséhez és az állománycsökkenés korai felismeréséhez. A megbízható állománynagyság-adatok segítik a természetvédelmi erőfeszítések céljainak meghatározását és a kipusztulás kockázatának felmérését. Az adatok következetes gyűjtése azonban nehézségekbe ütközik a távoli, vagy komplex domborzatú területeken – különösen a hamvas sólyom *(Falco concolor)* esetében, amelyet nemrég „sérülékeny" besorolásba helyeztek a különféle veszélyeztető tényezők és a csökkenő állományok miatt. Ez a tanulmány a faj költőpár-állományainak 12 éves idősoron alapuló populációs trendjeit elemzi, a faj elterjedési területén található 10 ország adatai alapján. A populációs előrejelzések finomítására a bizonytalanságot hibakategóriákkal leíró sztochasztikus szimulációt végeztünk bootstrap-módszerrel. A három generáció átlagát alapul vevő globális változás enyhe, -5,45%-os csökkenést mutatott, a konfidencia-intervallum –30% és +31% között volt. A legtöbb országban csökkenő tendencia figyelhető meg, különösen az Arab-félszigeten, ahol a nagyobb szigetek és a part menti területek állományai 20–25%-os visszaesést mutatnak. Ezzel szemben a sivatagi régiókban 20–30%-os növekedést tapasztaltunk, ami elsősorban a kutatások kiterjesztésének köszönhető.

Ez az átfogó tanulmány rámutat a monitorozási tevékenység bővítésének és a koordinált erőfeszítéseknek a szükségességére a folyamatos állománycsökkenés megállítása érdekében, különös figyelmet fordítva a változatos környezeti feltételek között élő, sebezhető populációkra.

Kulcsszavak: költőállományok, elterjedési terület, monitorozás, sztochasztikus szimuláció, csökkenés

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Introduction

Monitoring bird populations is essential for understanding their demographic trends and detecting declines before they become critical (Bibby *et al.* 2000, Gregory *et al.* 2004, Inger *et al.* 2015, Rosenberg *et al.* 2019). Accurate population estimates in wildlife conservation and management enable the assessment of conservation status, prediction of extinction risks, and guidance in prioritising protection efforts (Nunney & Elan 1994, Brouwer *et al.* 2003, Fagan & Holmes 2006, Blanco *et al.* 2014). These counts form the basis for classifying species into various threat categories, ranging from Least Concern to Critically Endangered (IUCN 2021). Long-term monitoring is particularly valuable in this context, as it provides insights into population fluctuations, facilitating the implementation of targeted conservation strategies and well-informed management decisions (Gregory *et al.* 2004, Donald *et al.* 2007). However, monitoring becomes more challenging for small and fragmented populations, particularly those in harsh, rugged, or less accessible terrains (Gregory *et al.* 2004, Kadry *et al.* 2021). Environmental factors, security issues and logistical constraints often hinder the collection of reliable data, making it difficult to assess these populations consistently and accurately (Witmer *et al.* 2005, Field *et al.* 2007).

Access to reliable population data is essential for implementing national and international conservation agreements, such as the Convention on Migratory Species (CMS). As part of this framework, the International Single Species Action Plan (ISSAP) for the Sooty Falcon *(Falco concolor)* has been developed and put into action, aiming to guide conservation efforts for the species (Leonardi *et al.* 2024). As a migratory species, the Sooty Falcon depends on coordinated international efforts for tracking its movements and conserving its breeding and non-breeding habitats (Mellone 2021, Leonardi *et al.* 2024). This small falcon shows facultative colonial behaviour, forming dense aggregations mainly on islands, whereas the distance between pairs in arid and hyper-arid regions ranges from 5 to 10 km (Moreau 1969, McGrady *et al.* 2019, Goren *et al.* 2023).

The global conservation status of the Sooty Falcon on the IUCN Red List of Threatened Species was listed as Least Concern until 2008, when it was reclassified as Near Threatened (under Criteria C1+2a[ii]), largely due to population declines in Arabia Peninsula (BirdLife International 2008, Jennings 2010). After the second global inventory of the species (1,400–2,000 breeding pairs), the Sooty Falcon was reclassified as Vulnerable (C2a(ii)) in 2017 and has continued to decline (Gallo-Orsi *et al.* 2014, BirdLife International 2017). Sooty Falcons face a range of threats across their habitat, including urban, industrial, and energy development, disturbance by tourists and fishers, and the introduction of terrestrial predators (Leonardi *et al.* 2024). Additionally, colonial-nesting birds like the Sooty Falcon, which breed on islands, are particularly vulnerable due to that any negative impact affects multiple breeding pairs (Burger 1981, McGrady *et al.* 2019).

Historical data analysis highlights a series of highly inconsistent estimates, resulting from limited reliable information, large unexplored areas, and precise data being available only for the more accessible insular populations (Leonardi *et al.* 2024, 2026). This study aims to ascertain changes in the abundance of Sooty Falcon populations at global, country, and sub-country scales over the most recent three-generation period. To ensure reliable estimates, we employ a stochastic simulation with a conservative approach, minimizing the risk of overestimating the accuracy of population trend estimates (Lynch *et al.* 2013, Langlois Lopez *et al.* 2023). Our primary objective is to address the challenges of highly variable short-term population estimates while accurately interpreting negative trend results to assess extinction risk.

Methods

This study focuses on Sooty Falcon population trends, considering only breeding pairs and excluding non-breeding data in accordance with IUCN criteria (IUCN 2012). Generation length, a key factor in extinction risk assessment, is estimated at 4.1 years (Bird *et al.* 2020, IUCN 2021). Based on this measure, population changes were analysed over a 12-year period to evaluate the species' conservation status. We defined 2010–2022 as the reference period, with 2022 representing the most recent global population estimate (Leonardi *et al.* 2024).

Table 1. Parameters used in the analysis, which include two population counts per country/location, their corresponding years, and associated errors (see Methods)

1. táblázat Az elemzések során használt paraméterek, amelyek helyszínenként/országonként két populációs számlálást jelentettek, azok évei és a kapcsolódó hibák (lásd Módszertan)

Country/Location	Year 1	Year 2	Count 1	Count 2	Error 1	Error 2
Bahrain	1984	2020	15[1]	6[2]	N2	N2
Egypt	2007	2024	446[3]	335[4]	N4	N2
Wadi El Gemal	2004	2019	181[5]	135[6]	N2	N2
Western Desert	2013	2024	101[7]	123[8]	N2	N2
Eritrea	1962	2004	170[9]	230[10]	N3	N2
Israel	1983	2014	100[11]	80[12]	N2	N2
Jordan	2000	2022	101[13]	60[14]	N5	N5
Libya	1961	2021	6[15]	375[16]	N5	N4
Jaghboub region	2022	2024	105[17]	180[17]	N3	N3
Oman	2007	2014	42[18]	37[18]	N2	N2
Fahal	2007	2014	14[19]	10[19]	N2	N2
Daymaniyats	2007	2014	29[19]	12[19]	N2	N2
Saudi Arabia	2011	2022	320[20]	274[21]	N3	N2
Al-Wajh Bank	1992	2022	77[22]	66[23]	N3	N2
NEOM islands	1992	2022	65[22]	54[24]	N3	N3
UAE	1994	2010	25[25]	6[26]	N2	N2
Yemen	2004	2013	85[27]	58[28]	N4	N4

[1] Nightingale & Overy 1987, [2] H. King in Leonardi *et al.* 2024, [3] A. Sandor in Leonardi *et al.* 2024, [4] Habib *et al.* 2026, [5] Coles & Williams 2004, [6] Habib 2019, [7] Salama *et al.* 2020, [8] Habib *et al.* 2026, [9] Clapham 1964, [10] Semere *et al.* 2008, [11] Frumkin & Pinshow 1983, [12] Goren *et al.* 2023, [13] F. Khoury in Leonardi *et al.* 2024, [14] L. El-Moghrabi and F. Khoury in Leonardi *et al.* 2024, [15] Booth 1961, [16] Riad *et al.* 2021, [17] Buirzayqah *et al.* 2026, [18] McGrady *et al.* 2018, [19] McGrady *et al.* 2023, [20] M. Shobrak in Leonardi *et al.* 2024, [21] L. Calabrese in Leonardi *et al.* 2024, [22] Gaucher *et al.* 1995, [23] Calabrese *et al.* 2026, [24] Darby Foster *et al.* 2026 [25] Shah *et al.* 2008, [26] Aspinall 2010, [27] Jennings & Sadler 2007, [28] O. Al Saghier in Leonardi *et al.* 2024.

Ultimately, the observed relative change reflects variation over a three-generation period for the species.

The most dependable way to analyse population trends is to compare at least two well-supported estimates over time (Brouwer *et al.* 2003, *Table 1*). Data on population counts were obtained from 10 countries, encompassing the majority of the breeding range of the Sooty Falcon *(Figure 1, Table 1)*. The historical analysis reveals that numerical inconsistencies still persist to some extent in Chad, Djibouti, Iran, Kuwait, and Pakistan, while Sudan shows a complete absence of data (Leonardi *et al.* 2026). However, with the latest global population estimate of 1,149–1,597 breeding pairs, the countries excluded from this study would represent at least 3–4% of the total (Leonardi *et al.* 2024). During the preparation of the ISSAP in 2013 and 2022, several estimates were obtained through questionnaires submitted to species experts, in addition to a bibliographic review (Leonardi *et al.* 2024). For countries with multiple estimates, the most accurate ones were selected *(Table 1)*. Several highly important sample areas for Sooty Falcon conservation, which have been repeatedly monitored, were also included in the analysis *(Table 1, Figure 1)*.

A stochastic simulation was performed for each population to incorporate uncertainty in the population counts (Lynch *et al.* 2013, Langlois Lopez *et al.* 2023). Error classes were defined with increasing ranges: N1 (0.00–0.05), N2 (0.05–0.10), N3 (0.10–0.25), N4 (0.25–0.50), and N5 (0.50–1.00). Classes N1 and N2 represent error margins of 0–5% and 5–10% in the counts, while N3, N4, and N5 indicate error margins of 10–25%, 25–50%, and 50–100%, respectively (Langlois Lopez *et al.* 2023). The latter three classes correspond to "good", "medium", and "poor" in BirdLife International's accuracy/quality classification. Thus, compared to BirdLife's categorization, this approach is more conservative, reducing the risk of overestimating the accuracy of population trend estimates (Lynch *et al.* 2013, Langlois Lopez *et al.* 2023).

For each population count n, the fractional error is sampled from a uniform distribution. For example, if the error class for n_1 is N2, then:

$$\mathrm{error}_{n_1} \sim \mathrm{Uniform}(0.05,\ 0.10)$$

The standard deviation for the truncated normal distribution is then calculated as

$$\sigma_n = \left(\frac{\mathrm{error}_n}{2}\right) \cdot n$$

so that for n_1 and n_2 we have:

$$\sigma_{n_1} = \left(\frac{\mathrm{error}_{n_1}}{2}\right) \cdot n_1 \quad \text{and} \quad \sigma_{n_2} = \left(\frac{\mathrm{error}_{n_2}}{2}\right) \cdot n_2$$

To ensure that negative population counts are avoided, the adjusted counts n'_1 and n'_2 are sampled from truncated normal distributions defined by

$$n_1' \sim TruncNorm\left(a = -\eta_1/\sigma_{n_1},\ b = \infty,\ \mu = \eta_1,\ \sigma = \sigma_{n_1}\right)$$

$$n_2' \sim TruncNorm\left(a = -\eta_2/\sigma_{n_2},\ b = \infty,\ \mu = \eta_2,\ \sigma = \sigma_{n_2}\right)$$

Assuming exponential growth (or decline) between the two observation years, the finite rate of population change, denoted by λ, is calculated as:

$$\lambda = \left(\frac{n_2'}{n_1'}\right)^{\frac{1}{\text{Year2}-\text{Year1}}}$$

To project the population to specific reference years, time gaps are defined as:

$$\text{Gap1} = \text{Year1} - \text{ref\_year\_start} \quad \text{and} \quad \text{Gap2} = \text{ref\_year\_end} - \text{Year2}$$

The corresponding fractional change factors are computed by

$$\text{Change1} = \lambda^{\text{Gap1}} \quad \text{and} \quad \text{Change2} = \lambda^{\text{Gap2}}$$

The estimated population for the reference year preceding Year1 is then obtained by back-projecting using

$$\text{Population at ref\_year\_start} = \frac{n_1'}{\text{Change1}}$$

and the population for the reference year following Year2 is estimated by

$$\text{Population at ref\_year\_end} = n_2' \cdot \text{Change2}$$

The relative change in population between these two reference years is finally calculated as

$$\text{Relative Change} = \frac{\text{Population at ref\_year\_end} - \text{Population at ref\_year\_start}}{\text{Population at ref\_year\_start}}$$

In order to account for uncertainty, this entire procedure is repeated over 50,000 iterations using a bootstrap simulation. The resulting distributions for λ, the projected populations, and the relative change are summarized by computing mean values and 95% confidence intervals, typically defined by the 2.5th and 97.5th percentiles of the bootstrap distribution. To prevent skewed mean statistics, counts outside these quantiles were excluded, reducing the influence of extreme values (Langlois Lopez *et al.* 2023). The analyses were conducted using R version 4.0.4 (R Core Team 2020).

Results

Global population trend

The global average change over three generations indicates a slight decrease of -5.45% *(Table 2)*. While this percentage may appear low, the confidence intervals are broad, ranging from -30% to +31% *(Table 2)*. For 2022, the estimated number of pairs is 1,204 (95% CI: 1,053–1,360), with a global finite rate of change of 0.99 *(Table 2)*. As expected for fragmented populations, smaller demes (< 30 breeding pairs) are more vulnerable to negative changes, with declines ranging from 25% to 70% *(Tables 1, 2)*.

Table 2. Changes in Sooty Falcon abundance across populations over the three-generation period (2010–2022), represented by the estimated number of breeding pairs at the start and end of the period, along with the corresponding percentage change and finite rate of change (λ)

2. ábra A hamvas sólyom állományának változása az egyes populációkban a három generációnyi időszakban (2010–2022), a költőpárok becsült száma az időszak elején és végén, valamint a megfelelő százalékos változás és a változás végső mértéke (λ)

	Breeding pairs 2010 Mean (95% CI)	**Breeding pairs 2022 Mean (95% CI)**	**Three-gen change (%) Mean (95% CI)**	**Finite rate of change (λ) Mean (95% CI)**
Bahrain	8 (7, 8)	6 (5, 6)	-26.3 (-28.9, -23.6)	0.98 (0.97, 0.98)
Egypt	423 (285, 553)	346 (317, 373)	-16.2 (-35.3, +15.3)	0.98 (0.96, 1.01)
Wadi El Gemal	161 (152, 170)	127 (116, 139)	-20.8 (-27.4, -13.7)	0.98 (0.97, 0.99)
Western Desert	96 (86, 105)	119 (111, 126)	+24.2 (+10.4, +39.4)	1.02 (1.01, 1.03)
Eritrea	240 (219, 262)	263 (229, 299)	+9.2 (+3.5, +15.9)	1.01 (1.00, 1.01)
Israel	82 (77, 88)	76 (68, 83)	-8.3 (-11.9, -4.4)	0.99 (0.99, 1.00)
Jordan	77 (31, 121)	61 (17, 106)	-18.5 (-64, -58.1)	0.98 (0.92, 1.04)
Libya[1]	173 (110, 234)	403 (247, 560)	+133 (+97, +197)	1.07 (1.06, 1.09)
Jaghboub region	6 (1, 22)	105 (86, 124)	+33.2 (+4.4, +117)	1.31 (1.15, 1.49)
Oman	40 (38, 42)	32 (27, 38)	-19.2 (-33, -3.3)	0.98 (0.97, 1.00)
Fahal	12 (12, 12)	7 (7, 7)	-43.8 (-44.7, 42.9)	0.95 (0.95, 0.95)
Daymaniyats	42 (38, 47)	4 (4, 5)	-89.6 (-92, -0.86)	0.88 (0.87, 0.89)
Saudi Arabia	325 (310, 340)	274 (265, 283)	-16 (-19, -13)	0.99 (0.98, 0.99)
Al-Wajh Bank	88 (60, 119)	62 (55, 70)	-26.3 (-52.3, 13.6)	0.99 (0.98, 1.00)
NEOM islands[2]	73 (52, 97)	54 (44, 64)	-23.9 (-50.6, -12.6)	0.99 (0.98, 1.00)
UAE	6 (6, 6)	2 (2, 2)	-66 (-69, -63)	0.91 (0.91, 0.92)
Yemen	66 (61, 72)	41 (37, 44)	-39 (-43, -35)	0.96 (0.95, 0.97)
Global[1]	**1273 (1035, 1514)**	**1206 (1053, 1358)**	**-5.45 (-30.4, +31.5)**	**0.99 (0.97, 1.02)**

[1] Global population totals are obtained by summing the individual populations of each country. As the results from Libya fall outside the 97.5th percentiles (see the Methods section), they have been excluded from the global estimation. To ensure this important population is still represented, the results from the Jaghboub region sub-population have been used instead.
[2] The counts refer to the islands of Baraqan, Yuba and Shushah

Country and sub-country trends

Among the 10 countries included in this study, 80% show a decline in breeding Sooty Falcon populations *(Table 2, Figure 1)*. Five countries (Egypt, Israel, Jordan, Oman, and Saudi Arabia) have declines ranging from 5% to 25%, while two (Bahrain and Yemen) experience declines of up to 50% *(Table 2, Figure 1)*. The UAE shows a decline exceeding 50% *(Table 1).* All populations in the Arabian Peninsula countries show a negative trend, especially those concentrated almost entirely in archipelagos and islands *(Table 2, Figure 1)*. The few instances of increment are primarily due to expanded exploration of remote areas, particularly desert regions in Libya and Saudi Arabia *(Table 2, Figure 1)*.

At the sub-country level, the same trend persists. Large islands, archipelagos, and coastal areas (Wadi El Gemal, Al-Wajh Bank, NEOM islands) have experienced a decline of ca. 20–25% *(Table 2)*. In contrast, desert regions (Western Desert, Jaghboub region) have shown an apparent increase of ca. 20–30%, primarily due to expanded territorial exploration *(Table 2)*.

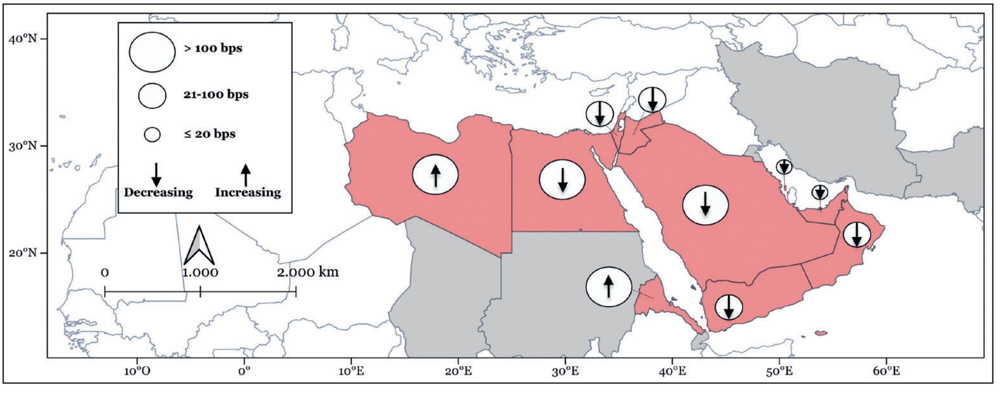

Figure 1. Sooty Falcon population sizes and trends across countries from 2010 to 2022. The size of each circle represents the population size, while arrows indicate population trends. Countries included in the study are highlighted in light red, whereas excluded countries appear in light grey (see Methods)

1. ábra A hamvas sólyom populációjának mérete és tendenciái az egyes országokban 2010 és 2022 között. Az egyes körök mérete a populáció méretét, míg a nyilak a populáció alakulását jelzik. A vizsgálatba bevont országok világospirossal, míg a kizárt országok világosszürkével vannak kiemelve (lásd Módszertan)

Discussion

In general, the global estimate for 2022 derived from the stochastic model is lower than the one proposed in the ISSAP, based on data compilation (Leonardi *et al.* 2024). This discrepancy is largely due to the conservative approach of the model, where data classified as 'good' by BirdLife are considered only in the third category (Langlois Lopez *et al.* 2023). Additionally, the estimate for Libya exceeds the 97.5th percentile of the bootstrap distribution, as indicated by the skewed means *(Table 2)*. This is due to the abrupt shift in estimates from fewer than 10 to 450–500 breeding pairs in this country (Booth 1961, Leonardi *et al.* 2024). The latter estimate from Riad *et al.* (2021), based on new data from the Jaghboub region (included in the model), appears to be somewhat optimistic. However, it emphasizes the important role that unexplored or poorly explored desert areas play in maintaining the stability of the global population. In the past decade, important stable populations have been identified in these uneven terrains: 101–123 breeding pairs in the Western Desert (Egypt), 85–180 in the Jaghboub region (Libya), 15 in the Dakhla Oasis (Egypt), and 19–42 in the Hisma Desert (Saudi Arabia) (Salama *et al.* 2020, Buirzayqah *et al.* 2026, Foster *et al.* 2026, Habib *et al.* 2026). Given this complex context, the substantial difference between the global decline of -5.45% over 12 years and -18–20% over 10 years proposed in the ISSAP becomes understandable *(Table 2)*, Leonardi *et al.* 2024). The ample confidence interval for the global three-generation change, ranging from -30.4 to +31.5, indicates that the decline in Sooty Falcon breeding populations greatly varies across different parts of the range *(Table 2, Figure 1)*.

The global population of the Sooty Falcon remains far from stable, as 8 out of 10 countries show a negative trend *(Table 2, Figure 1)*. Notably, the steepest declines are observed in countries that (1) host small populations (<30 breeding pairs) and (2) are limited to archipelagos and islands *(Table 2, Figure 1)*. In contrast, countries where the species is also present in inland areas, such as Egypt and Saudi Arabia, have managed to offset population declines in coastal regions. Overall, this study confirms the ongoing population decline across the whole Arabian Peninsula, a trend first identified over a decade ago (BirdLife International 2008, Jennings 2010). The negative trends measured, some exceeding 50%, strongly suggest the imminent local extinction of the species in certain countries (UAE, Bahrain). In several countries, the decline appears more limited (e.g. Israel, Goren *et al.* 2023) *(Table 2)*, Nevertheless, monitoring still requires expanded coverage of unexplored areas and coordinated efforts (e.g. Jordan, Saudi Arabia, Foster *et al.* 2026, Khoury *et al.* 2026, Martins *et al.* 2026).

At the sub-country level, the difference between populations living in various environmental contexts becomes even more pronounced *(Table 2)*. The populations in the Oman archipelagos are the most vulnerable, showing negative trends that exceed those recently highlighted (McGrady *et al.* 2023) *(Table 2)*. Declines are more limited in other coastal areas of Egypt and Saudi Arabia *(Table 2)*. A negative trend is also observed in the island populations of Yemen, although recent reliable data is lacking, and the status of breeding pairs in the country's inland areas remains unknown (Leonardi *et al.* 2024) *(Table 2)*. In hyper-arid areas like the Western Desert and the Jaghboub region, a positive trend is observed, despite the numerical fluctuations that characterize these areas (*Table 2)* (Salama *et al.* 2020, Buirzayqah *et al.* 2026). While occasional negative events, such as the Daniel flood of 2023 in Libya, should be considered, these habitats undoubtedly undergo significant year-to-year changes that impact the settlement of breeding pairs and their productivity (Salama *et al.* 2020, Buirzayqah *et al.* 2026).

Conclusions

The overall objective of the *International Single Species Action Plan for the Sooty Falcon 2024–2036*, is to reduce the risk of extinction for the Sooty Falcon by halting the decline in its population. The plan aims at bring the species to a point where it qualifies for downlisting to at least *Near Threatened* status (Leonardi *et al.* 2024). The 12-year-long plan spans approximately three generations of the species and focuses on two key objectives: (1) protecting the species, (2) enhancing knowledge through monitoring and research (Leonardi *et al.* 2024). The results of this study highlight that research and conservation efforts should be focused on the local context while being coordinated at a supra-country level. This approach will enable the assessment of any potential positive global effects in the next generation. Local actions, such as the provision of nest boxes – particularly in island environments – can improve the productivity of breeding pairs (Calabrese *et al.* 2026). On a global scale, establishing a unified and unequivocal global registry of nesting sites is highly recommended. This would optimize monitoring efforts, provide a foundation for long-term population surveys, and enable effective evaluation of conservation actions at both local and global levels.

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