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Egypt's protected-area network at the land–sea interface: coastal reserve fragmentation, the 30×30 gap, and Lessepsian bioinvasion (1983–2022)

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Research Article

Keywords: coastal conservation, land–sea interface, marine protected areas, coastal wetlands, Lessepsian migration, marine bioinvasion, 30×30 target, Mediterranean and Red Sea

Posted Date: July 6th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10085000/v1

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Additional Declarations: No competing interests reported.

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Highlights

- Egypt's coastal and marine reserves form its smallest, most fragmented tier.
- Three desert flagships hold ~75% of the estate (Gini = 0.83), masking coastal gaps.
- Status-quo growth leaves Egypt ~16 points short of the 30×30 target by 2030.
- Aquatic taxa dominate 281 aliens, fingerprinting the Suez Canal invasion corridor.
- Priority must shift to coastal MPAs, connectivity, OECMs and integrated coastal management.

Abstract

Coastal and marine ecosystems are among the most valuable and most rapidly degrading systems on Earth, and the area-based conservation that underpins their protection is now governed by the Kunming–Montreal Global Biodiversity Framework (KMGBF), whose Target 3 commits nations to conserve 30% of land and sea through ecologically representative, well-connected and effectively managed systems by 2030. The first global stocktake—the *Protected Planet Report 2024*—shows that the marine and connectivity dimensions, not area alone, are now the binding constraint, with only 8.4% of the ocean protected. We present the first integrated, multi-decadal (1983–2022) assessment of Egypt's protected-area (PA) network that reads the system through the lens of the land–sea interface, combining official EEAA and CAPMAS datasets with structural-break detection, Lorenz/Gini inequality analysis, Monte-Carlo contingency testing and scenario-based trajectory projection. The network expanded from a single 778 km² reserve to 30 reserves spanning 141,137 km² (14.1% of national territory) in two pulses (mid-1980s and mid-2000s) separated by a fifteen-year plateau objectively dated by change-point analysis. Reserve size is extremely unequal (Gini = 0.83): three desert flagships hold roughly three-quarters of the estate, whereas the Mediterranean coastal lagoons and the Red Sea and Gulf of Aqaba reserves fall almost entirely within a tier of nine reserves averaging under 12 km². Under the status-quo trajectory Egypt reaches only ~14% by 2030, an implementation gap of ~16 percentage points. Of 75 assessed mammals, threat incidence did not differ between marine and terrestrial species, but the most severe

categories were exclusively terrestrial. An inventory of 281 alien species—dominated by aquatic animals (≈67% of invasive fauna)—fingerprints the Suez Canal as the corridor of the world's largest marine bioinvasion. We argue that Egypt's conservation priority must shift from desert-driven area accumulation to consolidating coastal and marine connectivity, representativeness, marine protected areas, other effective area-based conservation measures (OECMs) and integrated coastal-zone management.

Keywords: coastal conservation; marine protected areas; land–sea interface; Lessepsian bioinvasion; 30×30 target; protected-area connectivity; integrated coastal-zone management

1. Introduction

Coastal and marine ecosystems (reefs, lagoons, seagrass meadows, mangroves, deltas and the dune–wetland mosaics of the land–sea interface) concentrate a disproportionate share of global biodiversity and ecosystem services, yet they are also among the most heavily and pervasively altered systems on the planet; no part of the ocean is now free of human influence, and a large fraction is strongly affected by multiple simultaneous pressures (Halpern et al., 2008). Area-based conservation principally networks of protected areas (PAs) and, increasingly, other effective area-based conservation measures (OECMs) remains the cornerstone instrument for slowing biodiversity loss, providing refugia for threatened species, safeguarding ecosystem services and maintaining ecological connectivity across fragmented seascapes and coastlines (Geldmann et al., 2013; Watson et al., 2014). Against a backdrop of contemporary extinction rates estimated at 100–1,000 times the pre-human background (Ceballos et al., 2015; Díaz et al., 2019), the adequacy of these networks at the coastal and marine margin has become a central question for conservation science and management.

The policy context was transformed in December 2022, when the fifteenth Conference of the Parties to the Convention on Biological Diversity adopted the Kunming–Montreal Global Biodiversity Framework (KMGBF). Its headline Target 3 (widely known as "30×30") commits Parties to ensure that, by 2030, at least 30% of terrestrial, inland-water, *coastal and marine* areas are conserved through "ecologically representative, well-connected and equitably governed systems of protected areas and other effective area-based conservation measures" (CBD, 2022; IUCN, 2023). Crucially, Target 3 reframes success: area coverage is necessary but no longer sufficient, because the qualifying language elevates representativeness, connectivity and effective management to formal criteria (Maxwell et al., 2020; Visconti et al.,

2019). For coastal nations, the target is explicitly a land–sea commitment that cannot be met by terrestrial designations alone.

The first global evaluation of Target 3, the *Protected Planet Report 2024*, makes the magnitude of the remaining challenge explicit, and locates it largely in the marine and connectivity dimensions. As of 2024, 17.6% of land and inland waters but only 8.4% of the ocean lay within documented protected and conserved areas—an increase of less than half a percentage point in either realm since the framework was adopted (UNEP-WCMC & IUCN, 2024). Reaching 30% would require protecting a further 21.6% of the ocean within six years. More tellingly, the quality dimensions lag far behind area: only about 8.5% of land is both protected and connected, almost one-third of Key Biodiversity Areas remain entirely unprotected, and management effectiveness has been assessed for less than 5% of the protected surface (UNEP-WCMC & IUCN, 2024). The persistence of "paper parks"—legally designated areas that deliver little conservation in practice—is especially acute for small, under-resourced coastal and marine sites, reinforcing the conclusion that the next phase of conservation must be measured by ecological function, not hectares alone (Geldmann et al., 2019; Relano & Pauly, 2023).

Egypt occupies a strategically pivotal position at the junction of Africa and Asia, with an exceptionally long and varied coastline—roughly 3,000 km along the Mediterranean in the north and the Red Sea, Gulf of Suez and Gulf of Aqaba in the east. This land–sea interface spans Mediterranean coastal lagoons and wetlands (Burullus, Bardawil, Manzala), Red Sea fringing and patch reefs, mangrove stands and the world-renowned reef systems of the Gulf of Aqaba, set against hyper-arid deserts and the Nile Valley. These coastal systems harbour notable endemism and serve as critical corridors for Afro-Palearctic migratory birds and for marine fauna moving between the Red Sea and the Mediterranean (Bakr & Bahnassy, 2018; Leach et al., 2013). They are simultaneously the focus of Egypt's most intense development pressures—coastal tourism, urbanization, port expansion, aquaculture and the squeeze imposed by sea-level rise on low-lying deltaic coasts. Egypt's PA network has expanded markedly since the declaration of Ras Mohammed National Park—its first marine-coastal reserve—in 1983, yet the network's adequacy has rarely been evaluated at the system scale, and almost never through the coastal-marine lens or against the quality criteria that now define international success. Egypt narrowly missed the previous Aichi Target 11 (17% terrestrial coverage by 2020), and whether its network is structurally positioned to contribute to the land and sea components of 30×30 remains unknown (EEAA, 2016).

Two pressures make a coastal-marine evaluation urgent. First, the arid-coastal mammal faunas of the Saharo-Arabian realm face severe and intensifying threats: modelling of Afro-Arabian endemics projects that as much as 17% could be lost before 2050, with Sinai and the adjacent coast identified as a primary hotspot (Brito et al., 2014; Soultan et al., 2019). Second, Egypt sits astride the Suez Canal—the principal pathway of Lessepsian migration and the engine of the single largest marine bioinvasion on Earth (Galil et al., 2018). The IPBES thematic assessment (IPBES, 2023) documented more than 37,000 established alien species globally, of which over 3,500 are harmful; invasive alien species are a contributing factor in 60% of recorded global extinctions and impose costs exceeding US$423 billion annually. Quantifying the scale and taxonomic structure of Egypt's alien biota (and the dominance of marine introduction pathways within it) is therefore of regional and global relevance for coastal and marine management.

Against this backdrop, previous Egyptian studies have largely been confined to individual reserves or single taxonomic groups, lacking the system-scale, multi-decadal and quantitatively rigorous treatment needed to inform adaptive coastal planning (Leach et al., 2013; EEAA, 2016). The present study addresses this gap by providing an integrated assessment of Egypt's PA network from 1983 to 2022, read explicitly through the land–sea interface. We pair conventional description with a suite of advanced analytics designed to interrogate network quality, and we ask four questions: (1) What are the temporal dynamics of network expansion, and can distinct phases be detected objectively? (2) How equal is the distribution of conservation effort among reserves, and where do coastal and marine sites sit within that structure? (3) Given observed trajectories, is Egypt positioned to approach 30×30 across land and sea, and what is the implementation gap? (4) What is the threat structure of Egyptian mammals (marine versus terrestrial) and what is the scale and composition of biological invasions at the coastal-marine margin? In answering these questions we aim to reorient Egypt's conservation narrative from the accumulation of desert area toward the consolidation of ecological quality at its coasts.

2. Materials and Methods

2.1 Data sources and compilation

The analysis integrates official national datasets spanning four decades (1983–2022). Protected-area records (establishment dates, ecosystem and administrative region, and area coverage km²) were obtained from the Egyptian Environmental Affairs Agency (EEAA)

protectorates database, cross-referenced with the *Annual Bulletin of Environment Statistics* issued by the Central Agency for Public Mobilization and Statistics (CAPMAS, 2024). To support the coastal-marine reading, each reserve was additionally assigned to a broad realm (coastal/marine (Mediterranean, Red Sea, Gulf of Suez and Gulf of Aqaba shorelines, lagoons and islands) or inland/desert) on the basis of its georeferenced position (Fig. 1). Mammalian conservation-status data (75 species classified as marine or terrestrial) followed national Red List categories. The alien and invasive species inventory was compiled across kingdoms (plants, animals, fungi, bacteria, viruses and chromista) and, within animals, to major taxonomic groups, with each animal group additionally flagged by aquatic versus terrestrial affinity. National coverage percentages were computed relative to Egypt's land area of 1,001,450 km².

We report the national protected-area figure (14.1%; EEAA/Ministry of Environment) alongside the globally standardized value derived from the World Database on Protected Areas (WDPA; ~13.1% for 2021), because the two are computed under different conventions and a transparent reconciliation is required for international comparison (UNEP-WCMC & IUCN, 2024). All regional comparators use national-land coverage on a common WDPA basis.

2.2 Temporal dynamics and objective phase detection

Cumulative reserve count, total area and national percentage were assembled as annual time series. Beyond descriptive growth-rate calculation, we applied multiple structural-break detection to locate expansion phases objectively. Annual cumulative area was modelled as a piecewise-stationary series and segmented using dynamic-programming change-point detection (Bai & Perron, 1998, 2003; Truong et al., 2020), with the number of breakpoints selected to capture the dominant transitions. Annual percentage growth was computed as the year-on-year relative change in cumulative coverage. This approach replaces visual identification of inflection points with a reproducible, data-driven segmentation.

2.3 Size inequality and network concentration

To quantify how evenly conservation effort is distributed among reserves we computed the Lorenz curve and Gini coefficient of reserve areas, a formal inequality framework previously applied to protected-area systems (Barnes et al., 2015). The Gini coefficient ranges from 0 (all reserves equal in size) to 1 (maximal inequality). We complemented this with a Pareto

(cumulative-contribution) analysis identifying the minimum set of reserves accounting for 80% of the protected estate, and with a *k*-means classification of reserves by absolute area and relative contribution, with the number of clusters informed by the size structure of the network (Margules & Pressey, 2000). The realm assignment (Section 2.1) was then overlaid on the resulting size structure to locate coastal and marine reserves within the network hierarchy.

2.4 Trajectory toward the 30×30 target

We projected national coverage to 2030 under three transparent scenarios: (i) a status-quo trajectory extrapolating the recent (2012–2022) linear trend; (ii) a long-run trajectory based on the mean annual gain across the full 1983–2022 record; and (iii) the constant-rate path required to reach 30% by 2030. The implementation gap was defined as the difference between the status-quo projection and the 30% target in 2030, expressed both in percentage points and in the additional area (km^2) that would need to be conserved. Because Target 3 is a combined land–sea commitment, we interpret the terrestrial gap alongside the markedly lower global marine baseline (8.4%; UNEP-WCMC & IUCN, 2024), which frames the additional marine effort required of coastal states such as Egypt.

2.5 Biodiversity and bioinvasion assessment

Associations between mammal type (marine vs. terrestrial) and threat status were examined with contingency analysis. Because several expected cell counts were below five—violating the assumptions of the asymptotic chi-square test, we used a Monte-Carlo (permutation) chi-square test with 20,000 randomizations for the full category table, and a complementary test on a biologically meaningful three-level collapse (not threatened; threatened; severely threatened). Adjusted standardized residuals identified the cells contributing most to any association. A severity-weighted threat index (0 = not threatened to 5 = extinct in the wild) was reported as a descriptive summary. The taxonomic composition of invasive species was analysed using proportional and hierarchical breakdowns; aquatic versus terrestrial affinity of invasive animals was tabulated to evaluate the role of marine introduction pathways through the Suez Canal.

2.6 Software and reproducibility

All analyses were conducted in open-source environments (R and Python). Change-point detection used dynamic-programming segmentation; inequality metrics, permutation tests and trajectory projections were implemented with standard numerical libraries. Figures were

produced at publication resolution with consistent typography and colour. Analysis scripts and derived datasets are available from the corresponding author to support reproducibility.

3. Results

3.1 Current status and temporal evolution of the network

As of 2022, Egypt's protected-area network comprised 30 reserves covering 141,136.7 km², equivalent to 14.1% of national territory (Table 1; Fig. 1). The spatial distribution spans six broad regions, from Mediterranean and Nile-associated wetlands to the Red Sea coast, the Gulfs of Suez and Aqaba, Sinai and the Western Desert . The temporal record (Table 2) reveals a markedly non-linear growth history. Cumulative coverage rose from a single 778.2 km² reserve in 1983 to 62,733.5 km² (6.2%) by 1989, surged again to 135,292.7 km² (13.5%) by 2007, and has since changed little, reaching 14.1% by 2021–2022 (Fig. 2).

Table 1. The 30 reserves of Egypt's protected-area network, keyed to the georeferenced numbers in Fig. 1.

(1) Ras Mohamed	(7) El Zaranik & Sabkha	(13) Wadi El Rayan	(19) Burullus	(25) Northern Islands
(2) Nabaq	(8) Ashtum El Gamil	(14) Wadi Sannur Cave	(20) Nile River Islands	(26) El Dababya
(3) Abu Galum	(9) El Omayed	(15) Wadi El Asyuti	(21) Wadi Degla	(27) El Gilf El Kebir
(4) Taba	(10) Petrified Forest	(16) El Bardawil	(22) Siwa	(28) El Salloum
(5) Saint Katherine	(11) El Hassana Dome	(17) Wadi El Allaqi	(23) White Desert	(29) El Wahat El Bahariya
(6) Al Ahrash	(12) Qarun	(18) Elba	(24) Wadi El Gemal	(30) Gebel Kamil Crater

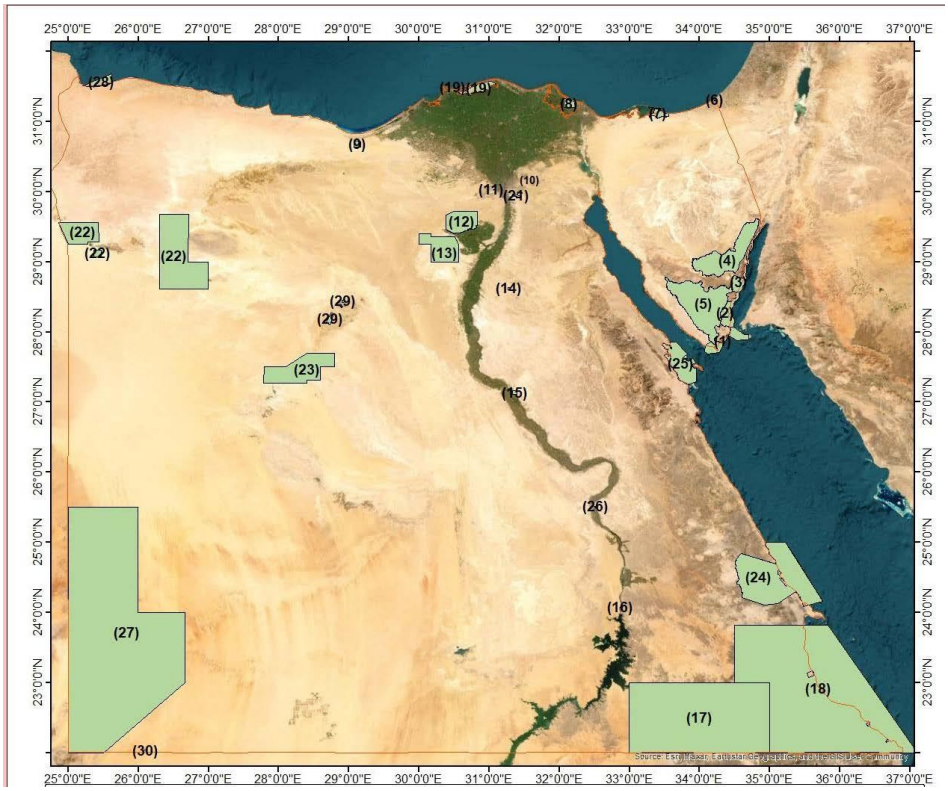


Fig. 1. Spatial distribution of Egypt's protected-area network: georeferenced boundaries of the 30 nature reserves across six biogeographic regions, keyed to Table 1 (updated from EEAA, 2022). Coastal and marine reserves cluster along the Mediterranean shore and the Red Sea–Gulf of Aqaba margin, whereas the largest reserves occupy the hyper-arid interior.

Objective change-point analysis of the annual coverage series detected two dominant structural breaks, bracketing the foundational expansion of the mid-to-late 1980s and the major pulse of the mid-2000s, and confirming a prolonged post-2007 plateau (Fig. 3A). Annual growth-rate analysis (Fig. 3B) isolated the same dynamics: an exceptional surge in 1986 (exceeding 3,000%, when Elba and other large desert reserves were gazetted), a secondary pulse of roughly 56% in 2007, and near-zero growth thereafter. A strong positive association between reserve number and total coverage ($r \approx 0.95$) indicates that expansion was achieved chiefly by adding new reserves rather than enlarging existing ones.

Table 2. Milestones in the expansion of Egypt's protected-area network, 1983–2022, with the expansion phase identified by change-point analysis.

Year	Cumulative area (km²)	National coverage (%)	Expansion phase
1983	778.2	0.08	Foundation (Ras Mohammed)
1989	62,733.5	6.2	First expansion pulse
2007	135,292.7	13.5	Second expansion pulse
2022	141,136.7	14.1	Post-2007 plateau

National coverage computed relative to Egypt's land area of 1,001,450 km².

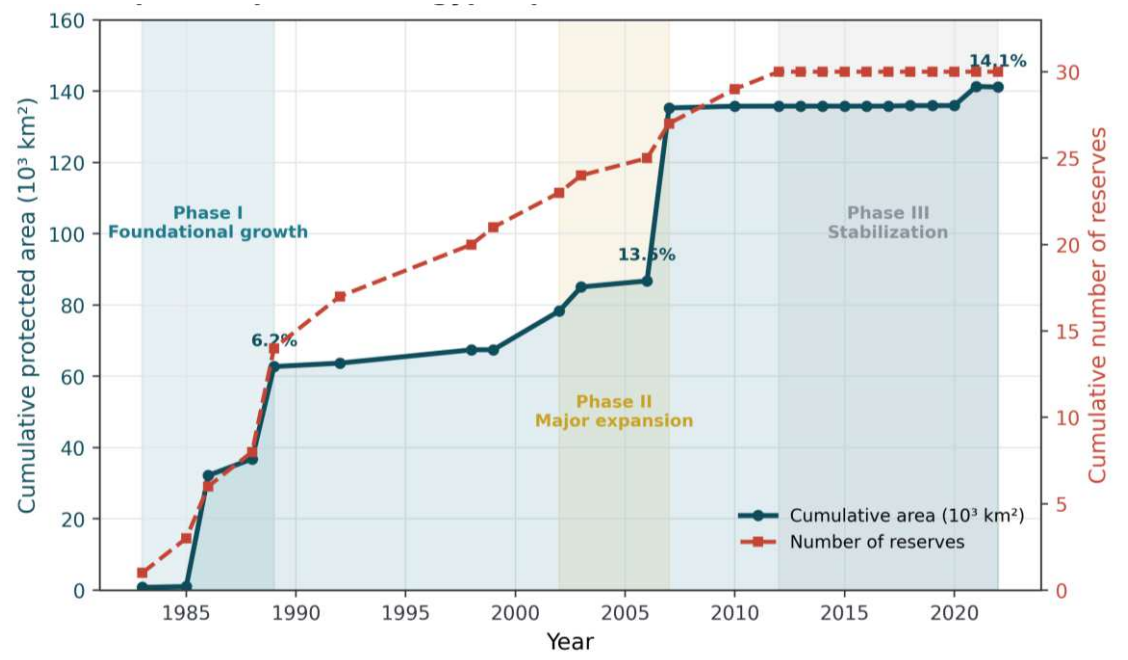


Fig. 2. Temporal expansion of Egypt's protected-area network (1983–2022). Cumulative protected area (left axis, filled line) and cumulative number of reserves (right axis, dashed line), with the expansion phases shaded. National coverage percentages are annotated at key milestones.

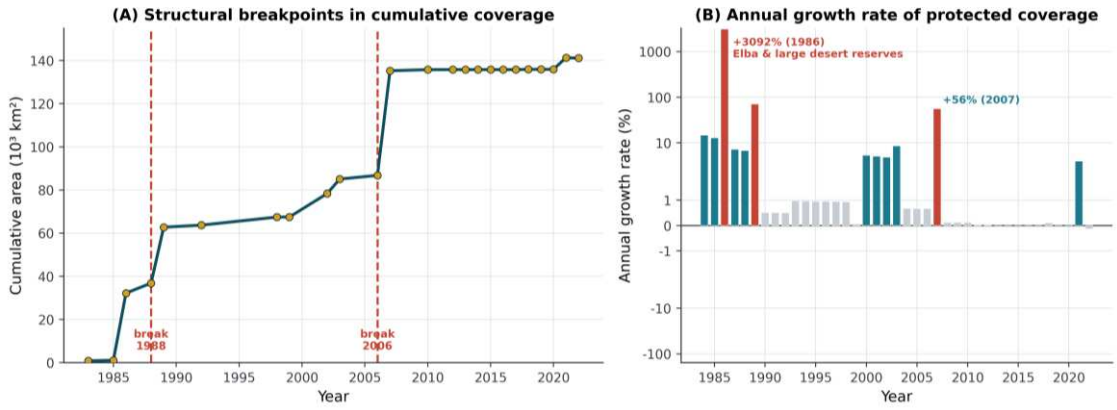


Fig. 3. Growth trajectory and change-point structure. (A) Dynamic-programming detection of structural breakpoints in cumulative coverage (dashed lines). (B) Annual growth rate of protected coverage on a symmetric-log scale, highlighting the 1986 and 2007 expansion pulses against an otherwise quiescent record.

3.2 Size inequality, concentration and the position of coastal reserves

Conservation effort is distributed with pronounced inequality among reserves. The Lorenz curve departs far from the line of equality, yielding a Gini coefficient of 0.83 (indicating near-maximal size inequality within the network (Fig. 4A). Concentration analysis shows that the four largest reserves alone account for more than 80% of the total protected estate (Fig. 4B), with El Gilf El Kebir (47,941.3 km²; 33.9%) and Elba (35,609.5 km²; 25.2%) together representing the majority of conserved land. The Pareto analysis (Fig. 5) confirms this flagship-dominated structure.

A *k*-means classification recovered three reserve types (Table 3, Fig. 6): a small cluster of three flagship reserves (mean area ≈ 35,539 km²; ~25% relative contribution each); 18 medium reserves (mean ≈ 1,920 km²); and nine very small reserves (mean ≈ 11.8 km²; <0.4% contribution each). Critically for coastal conservation, the realm overlay reveals a sharp spatial bias in this hierarchy: the flagship tier that dominates national coverage lies entirely in the hyper-arid interior, whereas Egypt's coastal and marine reserves—the Mediterranean lagoons (Burullus, El Bardawil, El Zaranik) and the Gulf of Aqaba reefs (Taba, Abu Galum, Nabaq)—fall overwhelmingly within the small-reserve cluster. The coexistence of a few very large desert reserves with many sub-12 km² coastal and wetland reserves is the structural signature underlying the high Gini coefficient, and it means that the biodiversity-rich land–sea interface is precisely the most fragmented and least buffered part of the network, with direct implications for edge effects and connectivity (Section 4).

Table 3. k-means classification of reserves by size and relative contribution to network coverage.

Cluster	Mean area (km²)	Mean relative area (%)	n	Type
I	35,539.3	25.13	3	Large flagship (desert)
II	1,919.6	1.36	18	Medium
III	11.8	0.31	9	Small (coastal/wetland)

Cluster labels reassigned in ascending order of mean area. Realm descriptors reflect the predominant character of reserves in each cluster (see Section 2.1).

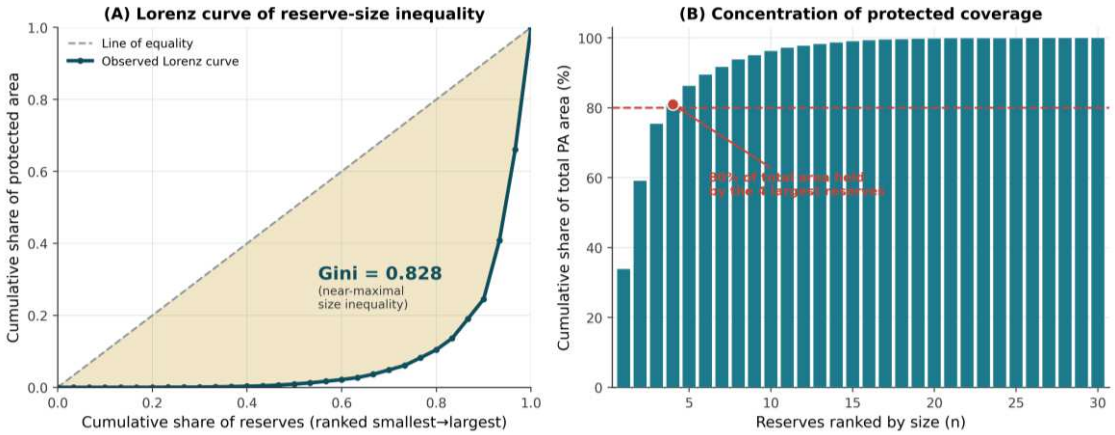


Fig. 4. Size inequality and spatial concentration of the reserve network. (A) Lorenz curve of reserve areas with the Gini coefficient; the shaded area between the curve and the line of equality measures inequality. (B) Cumulative share of total protected area as reserves are added largest-first, showing that four reserves reach the 80% threshold.

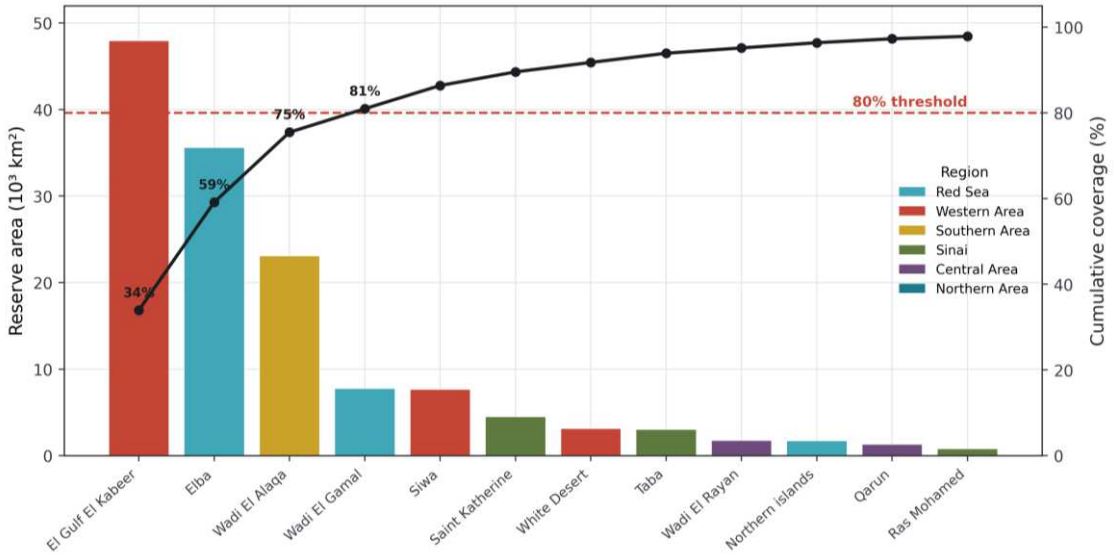


Fig. 5. Pareto analysis of reserve contributions. Individual reserve areas (bars, coloured by region) and cumulative coverage (line); the 80% threshold is reached within the four largest reserves, underscoring the network's dependence on a small number of inland flagship sites.

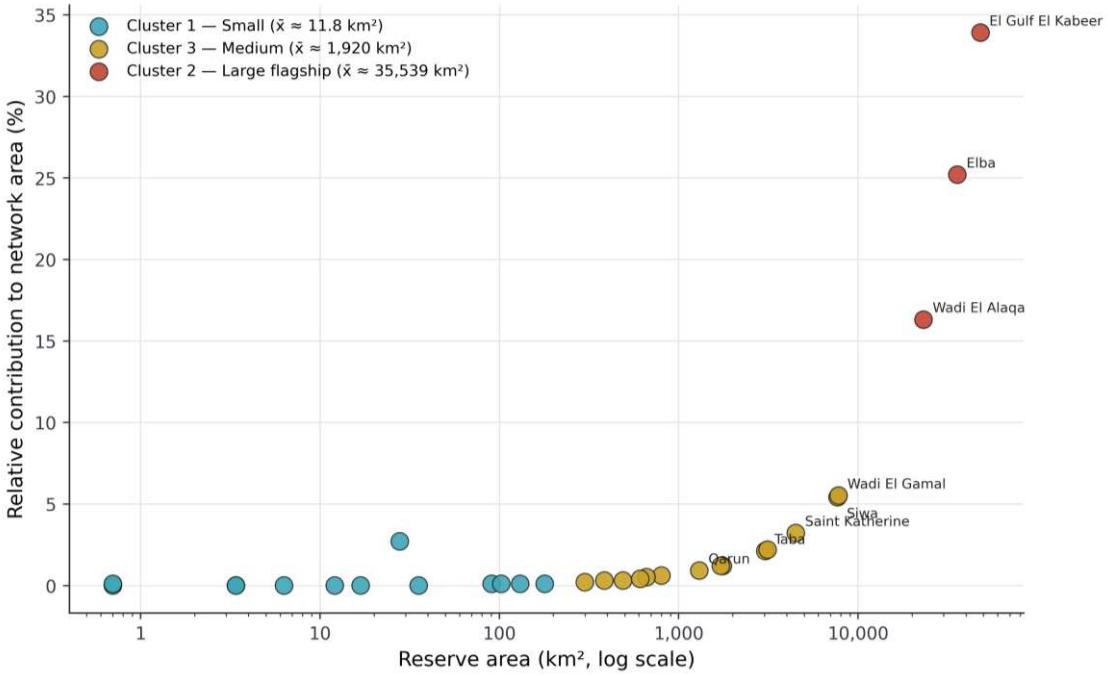


Fig. 6. k-means typology of reserves. Reserves classified by absolute area (log scale) and relative contribution to network coverage, resolving small (coastal/wetland), medium and large-flagship (desert) clusters.

3.3 Regional and global context

Placed in regional context, Egypt's coverage is comparatively strong (Table 4). On the common WDPA basis, Egypt (~13.1%, or 14.1% on the national basis) exceeds Tunisia (7.9%), Saudi Arabia (4.8%), Algeria (4.6%), Jordan (4.5%), Morocco (2.2%) and Libya (0.1%). Egypt nonetheless sits below the global terrestrial mean of 17.6% and far below the 30% Target-3 threshold and, like its regional neighbours, far below the level of marine protection implied by the ocean component of 30×30 framing both its regional leadership and the distance still to travel at the coastal-marine margin.

Table 4. Terrestrial protected-area coverage of Egypt and regional comparators. Values on a common WDPA/World Bank basis (2021); Egypt also shown on its national basis.

Country	Terrestrial PA coverage (% land)
Egypt (national basis)	**14.1**
Egypt (WDPA basis)	**13.1**
Tunisia	7.9
Saudi Arabia	4.8
Algeria	4.6
Jordan	4.5
Morocco	2.2
Libya	0.1

3.4 Trajectory toward the 30×30 target

Scenario projection indicates that Egypt is not on course to meet Target 3 under current dynamics (Fig. 7). Extrapolating the 2012–2022 trend yields a 2030 coverage of approximately 14%, essentially unchanged from today; even the more optimistic long-run trajectory reaches only ~17%. Closing the gap to 30% by 2030 would require a sustained acceleration far exceeding any rate observed since the mid-2000s. The resulting terrestrial implementation gap is approximately 16 percentage points—equivalent to conserving on the order of 157,000 km² of additional land within six years, an area larger than the entire current network. The marine shortfall is plausibly larger still: against a global ocean baseline of 8.4% (UNEP-WCMC & IUCN, 2024), meeting the sea component of 30×30 would demand a step change in marine and coastal designation that Egypt has not yet begun.

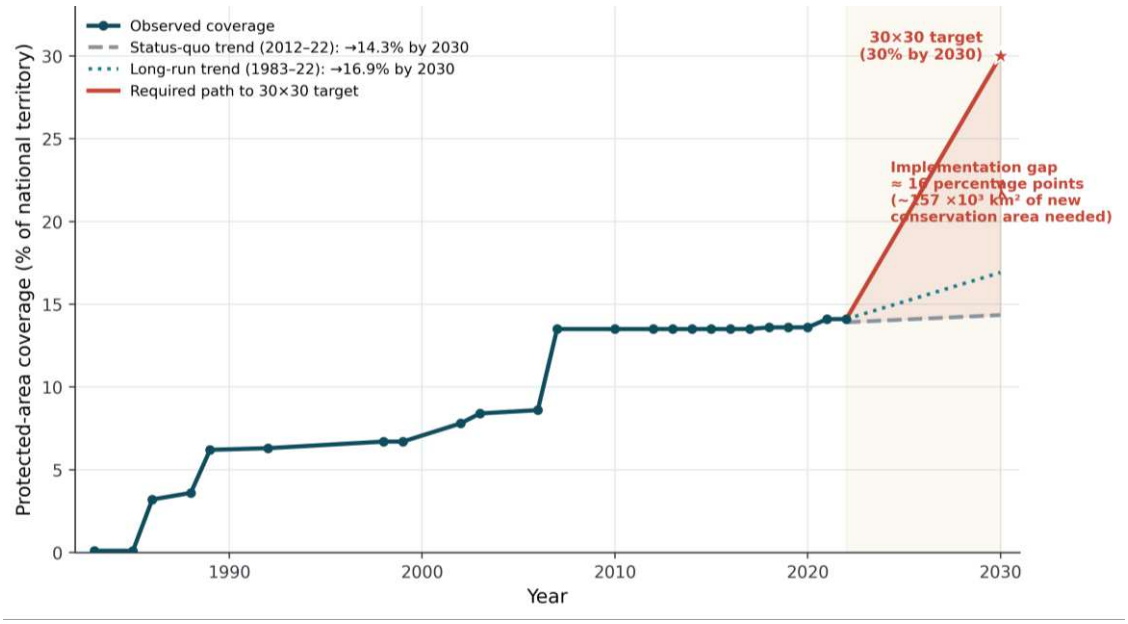


Fig. 7. Will Egypt reach the 30×30 target? Trajectory projection to 2030. Observed coverage with status-quo and long-run extrapolations, the constant-rate path required to reach 30% by 2030, and the resulting implementation gap (shaded).

3.5 Threat structure of the mammalian fauna

Of 75 assessed mammal species, 39 (52.0%) were classified as not threatened, while the remainder spanned categories from vulnerable to extinct in the wild, and 9 were data-deficient (Table 5). Restricting inference to the well-defined marine–terrestrial contingency table (Section 2.5.1), the proportion of species in a threat category did not differ significantly between marine (35.0%) and terrestrial (34.8%) mammals; the Monte-Carlo chi-square test across all categories was non-significant ($\chi^2 = 8.20$, $p = 0.135$), as was the collapsed three-level test ($\chi^2 = 1.51$, $p = 0.531$) (Fig. 8A). The biologically salient contrast is qualitative rather than in overall incidence: terrestrial mammals alone occupied the most severe categories—Critically Endangered and Extinct in the Wild together comprised ~7% of terrestrial species but were entirely absent among marine mammals (Fig. 8B). Adjusted residuals indicated only modest, non-significant cell-level deviations. These results temper, and refine, earlier interpretations of a strong marine–terrestrial divergence: incidence is comparable, but the upper tail of severity is exclusively terrestrial.

Table 5. Conservation-status assessment of Egyptian mammals, classified by type (marine + terrestrial = 75 species); see Section 2.5.1.

Threat status	Marine	Terrestrial	Total (reported)
Not threatened	10	29	39
Not seriously threatened	3	1	4
Vulnerable to extinction	3	10	13
Threatened with extinction	4	3	7
Critically threatened	0	2	2
Extinct in the wild	0	1	1
No information	0	9	9
Total	**20**	**55**	**75**

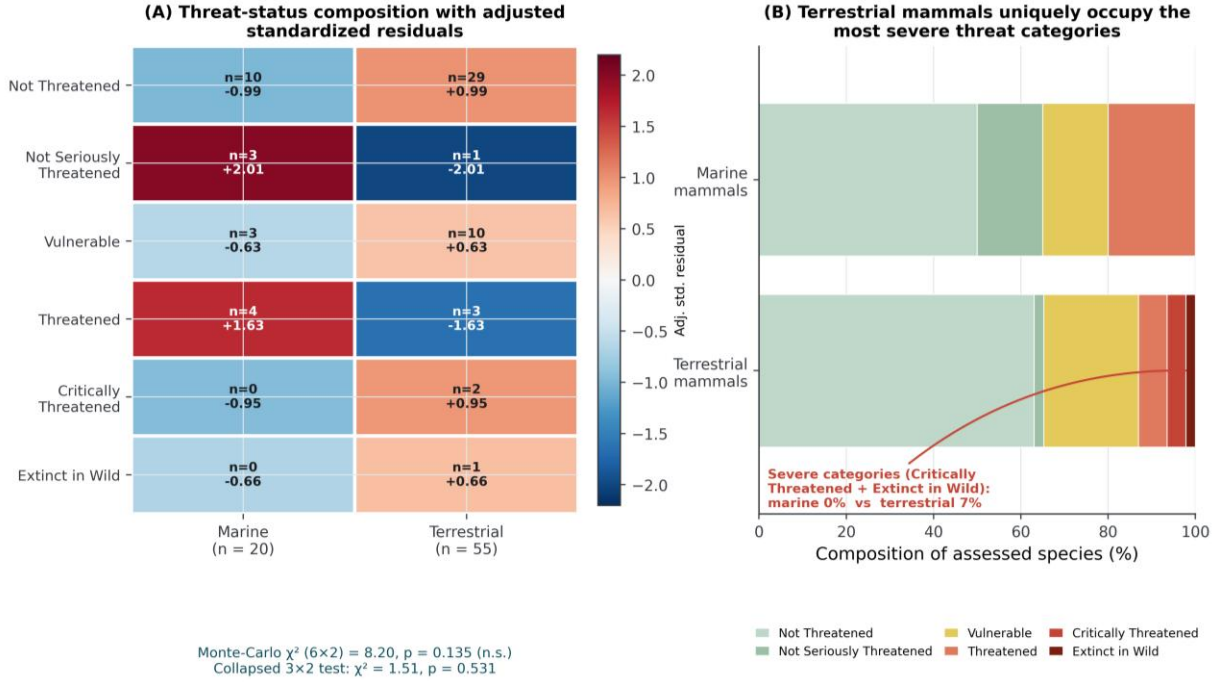


Fig. 8. Conservation-threat structure of Egypt's mammalian fauna. (A) Threat-status composition for marine and terrestrial mammals with adjusted standardized residuals; Monte-Carlo and collapsed-table tests are non-significant. (B) Proportional composition showing that the most severe categories (Critically Threatened, Extinct in the Wild) are exclusive to terrestrial mammals.

3.6 Scale and composition of biological invasions

The inventory documented 281 alien and invasive species across all major kingdoms (Table 6; Fig. 9A). Animals dominated (132 species; 47.0%), followed by plants (114; 40.6%), with smaller contributions from viruses (17), fungi (11), bacteria (6) and chromista (1). Among the 132 invasive animals, aquatic taxa accounted for roughly two-thirds: fish alone contributed 47 species (the single largest animal group), followed by insects (30), crustaceans (17) and molluscs (10) (Fig. 9B). The strong aquatic signal—spanning fish, crustaceans, molluscs, cnidarians and other marine invertebrates—is consistent with introduction via the Suez Canal, shipping and aquaculture, and identifies marine and coastal pathways as the principal vector of biological invasion in Egypt.

Table 6. Inventory of alien and invasive species across taxonomic groups (2022).

Taxonomic group	Number of species
Animals (total)	**132**
Fish	47
Insecta	30
Crustacea	17
Mollusca	10
Nematoda	6
Chordata	5
Cnidaria	3
Annelida	3
Mammals	3
Bryozoa	2
Reptilia	2
Amphibia	2
Arthropoda	1
Echinodermata	1

Plants	**114**
Viruses	**17**
Fungi	**11**
Bacteria	**6**
Chromista (algae)	**1**
Total	**281**

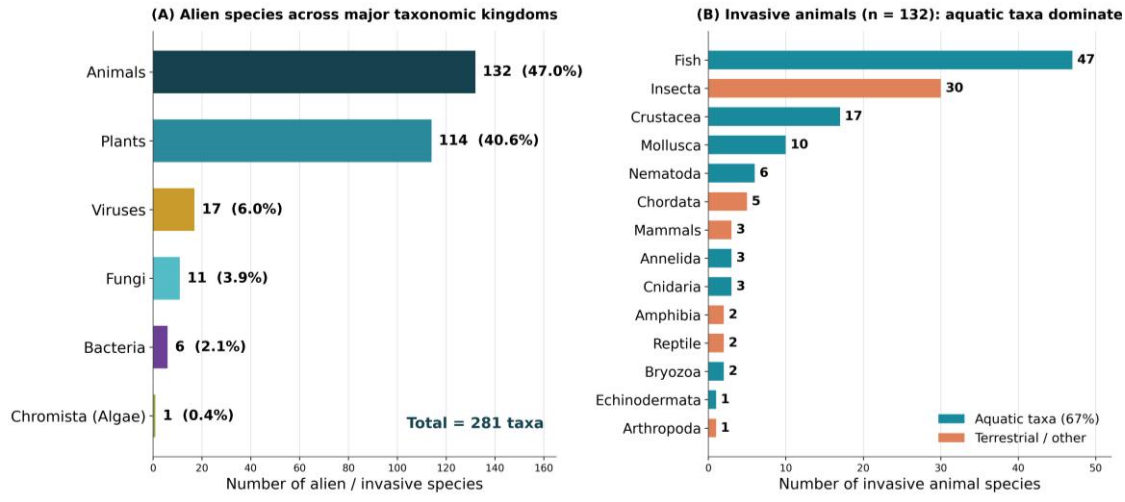


Fig. 9. Taxonomic structure of Egypt's 281 documented alien and invasive species. (A) Distribution across major kingdoms. (B) Breakdown of invasive animal species by subgroup, with aquatic taxa (~67% of invasive animals) highlighted, reflecting the dominance of Suez Canal–mediated marine introduction pathways.

4. Discussion

4.1 From desert area to coastal ecological quality

Our results portray a network that succeeded in the twentieth-century conservation objective—accumulating area—but that now confronts the twenty-first-century challenge of ecological quality, and nowhere more acutely than at the coast. Egypt assembled a 141,137 km² estate in two decisive pulses and has since plateaued for roughly fifteen years. Under KMGBF Target 3, coverage is only the entry criterion; representativeness, connectivity and management effectiveness determine whether a network delivers (CBD, 2022; UNEP-WCMC & IUCN, 2024). Egypt's plateau since 2007 therefore coincides precisely with the period in which international expectations shifted beneath it, leaving the network well-positioned on area yet untested on quality—and structurally weakest exactly where biodiversity value is highest.

The extreme size inequality we document (Gini = 0.83) is the network's most consequential structural feature, and its coastal implications are stark. That three flagship desert reserves hold roughly three-quarters of the estate confers genuine advantages—large reserves better retain interior-dependent species, buffer edge effects and accommodate range shifts under climate change (Brito et al., 2014). But it also means that national coverage statistics are highly sensitive to a handful of interior sites, while the many sub-12 km² reserves—which are disproportionately the Mediterranean lagoons, the Gulf of Aqaba reefs and the Nile-associated wetlands of high biodiversity value—are individually too small to be self-sustaining and are vulnerable to isolation. This is the configuration that connectivity science flags as fragile: without functional linkages, small coastal reserves behave as islands, and island-biogeographic theory predicts ongoing relaxation toward lower species richness (Saura et al., 2018). Globally, only about 8.5% of land is both protected and connected (UNEP-WCMC & IUCN, 2024); our findings strongly motivate a formal connectivity assessment (e.g., the Protected Connected indicator, ProtConn) of Egypt's coastal network as a priority next step, alongside an explicit accounting of the marine realm that national land statistics obscure.

4.2 The 30×30 implementation gap and the limits of expansion

The trajectory analysis delivers a sobering message: under status-quo dynamics Egypt will approach 2030 near 14% terrestrial coverage, leaving an implementation gap of roughly 16 percentage points—around 157,000 km² of new conservation area, larger than the entire existing network—while the marine component of the target remains essentially unaddressed. Achieving this through conventional state protected areas within six years is implausible given fiscal and land-use constraints in a country that is 92% desert with intense pressure on the arable Nile fringe and a rapidly developing coast (EEAA, 2016). This reframes the policy question. Rather than treating 30% as an area to be acquired, Egypt's most credible pathway combines three levers: recognizing other effective area-based conservation measures (OECMs) community-managed rangelands, Bedouin grazing reserves, military-restricted zones and, critically for the coast, managed coastal and marine areas, locally managed reef sites and fisheries closures that already deliver de facto conservation; improving the ecological performance of the existing estate so that protected hectares become effective hectares; and strategically adding representation in under-protected coastal, wetland and marine ecosystems rather than further enlarging already-vast desert reserves. OECMs in particular offer a route to count, and incentivize, conservation outcomes outside the formal PA system (IUCN, 2023; Maxwell et al., 2020).

4.3 Mammalian threats: incidence versus severity in an arid-coastal realm

Our reanalysis refines the mammalian picture. Where overall threat incidence is concerned, marine and terrestrial mammals did not differ significantly a result that contrasts with the global pattern in which marine mammals carry a higher threatened fraction (36% vs. 25%; Schipper et al., 2008) and which should be interpreted cautiously given the dataset's inconsistencies. The robust and biologically meaningful signal is in the upper tail of severity: the Critically Endangered and Extinct-in-the-Wild categories were occupied exclusively by terrestrial mammals. This is consistent with the drivers operating across the Saharo-Arabian realm, where aridification, overhunting, livestock competition and habitat conversion have driven severe range contractions and local extirpations of large desert mammals (Brito et al., 2014; Durant et al., 2014). Modelling of Afro-Arabian endemics projects up to 17% extinction by 2050, with Sinai a hotspot (Soultan et al., 2019) precisely the terrestrial systems most represented in Egypt's severe threat categories. The comparatively favourable position of marine mammals should not breed complacency: the Red Sea and Gulf populations of dugong and cetaceans depend on coastal seagrass and reef habitats that are concentrated in exactly the small, fragmented reserves identified above, and remain exposed to coastal development, vessel traffic and bycatch.

4.4 Biological invasions and Egypt's Lessepsian gateway

The inventory of 281 alien and invasive species, and especially the dominance of aquatic animals within it, situates Egypt at the epicentre of a globally significant bioinvasion process and at the heart of JCC's coastal-marine remit. The Suez Canal has been the principal corridor of Lessepsian migration since 1869, and the Mediterranean is now the most heavily invaded sea on Earth, with more than a thousand recorded marine aliens and continuing tropicalization (Galil et al., 2018). That fish, crustaceans and molluscs dominate Egypt's invasive animal fauna is the national fingerprint of this canal-mediated flux, and it intersects directly with the coastal management challenge: introduction nodes are ports, marinas, the canal corridor and aquaculture facilities along the very shores where conservation is weakest. The stakes are quantified by the IPBES (2023) assessment: invasive species contribute to 60% of recorded global extinctions and cost in excess of US$423 billion annually, with roughly 200 new aliens recorded worldwide each year. Two implications follow for Egypt. First, the count of 281 should be regarded as a lower bound and a snapshot; without systematic, repeated coastal

surveillance the true richness and its rate of increase are unknown. Second, because eradication of established marine invaders is rarely feasible, management should prioritize early detection and rapid response at introduction nodes (consistent with the prevention-first hierarchy that the IPBES assessment identifies as most cost-effective) embedded within an integrated coastal-zone management framework.

4.5 Toward effective, financed and representative coastal conservation

Synthesizing across our results, Egypt's conservation strategy should pivot from a metric of hectares to a metric of coastal and marine outcomes. Three priorities emerge. *Representation:* the network's desert-dominated composition leaves Mediterranean coastal wetlands, Nile systems and Red Sea marine habitats comparatively under-protected relative to their biodiversity value, and a formal ecoregion and seascape gap analysis should guide future designations, including new and enlarged marine protected areas. *Effectiveness:* with management effectiveness assessed for under 5% of protected land globally and the "paper park" risk acute for small, under-resourced coastal reserves and MPAs, Egypt should institutionalize periodic management-effectiveness evaluation (e.g., METT/RAPPAM) across its estate (Coad et al., 2015; Geldmann et al., 2019; Relano & Pauly, 2023). *Finance:* against a global biodiversity-finance gap on the order of US$700 billion annually, Egypt's national biodiversity-finance planning should explicitly fund coastal effectiveness, connectivity and invasion surveillance, not only designation. Embedding these priorities within an integrated coastal-zone management framework (one that reconciles tourism, fisheries, ports and conservation at the land–sea interface) would convert Egypt's strong area position into genuine ecological return for its coasts and seas.

4.6 Limitations

Some limitations qualify our conclusions. The source inventories required reconciliation (Section 2.5.1): we adopted the internally consistent marine–terrestrial mammal classification (75 species) and the 132 taxonomically assigned invasive animals, excluding an unreconcilable published aggregate of 86 mammals and 11 unassigned animal records; these well-defined subsets, analysed with exact and permutation methods appropriate to sparse counts, should be revisited once species-level records become available. The realm assignment of reserves is a broad coastal/marine-versus-inland classification based on georeferenced position rather than a habitat-resolved delineation, and our connectivity and representativeness inferences are structural—drawn from size distribution and regional composition—while direct spatial

analyses (ProtConn, ecoregion and seascape coverage) require reserve-boundary data and represent the most important next step. The invasive inventory is a single compilation and cannot characterize introduction rates or establishment trends, so the count is best read as a conservative snapshot. The trajectory projections are scenario-based extrapolations, not forecasts, and remain sensitive to future policy decisions, including the recognition of OECMs and the pace of marine designation.

5. Conclusions

Egypt has built one of the larger protected-area networks in North Africa and the Saharo-Arabian region, expanding from a single reserve in 1983 to 30 reserves covering 14.1% of its territory by 2022. Objective change-point analysis confirms that this growth occurred in two pulses separated by a long plateau, and that expansion has effectively stalled for fifteen years. The network is structurally dominated by a few flagship desert reserves (Gini = 0.83; four reserves hold over 80% of the estate), leaving the biodiversity-rich coastal lagoons, Red Sea reefs and Gulf of Aqaba reserves confined to a small, fragmented and potentially isolated tier at the land–sea interface. Under current dynamics Egypt is not on track for the 30×30 target, facing a terrestrial implementation gap of roughly 16 percentage points and an essentially unaddressed marine component. Its mammalian fauna shows comparable overall threat incidence across marine and terrestrial groups but a severe-threat tail that is exclusively terrestrial, signalling a small-species-at-the-brink crisis in the deserts even as coastal marine mammals depend on the most fragile reserves. An inventory of 281 alien species, dominated by aquatic animals, confirms Egypt's role as a global gateway for marine bioinvasion through the Suez Canal. Taken together, these findings argue for a decisive shift from accumulating desert area to consolidating coastal and marine ecological quality—advancing connectivity, representativeness and management effectiveness; expanding marine protected areas and recognizing coastal OECMs; instituting invasion early-warning at ports and the canal corridor; and aligning conservation finance within an integrated coastal-zone management framework. Such a reorientation would allow Egypt to translate its considerable area achievements into durable biodiversity outcomes at the coast, consistent with the Kunming–Montreal Global Biodiversity Framework.

Declarations

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability

The datasets analysed in this study were compiled from publicly available official sources (the EEAA protectorates database and the CAPMAS Annual Bulletin of Environment Statistics). Derived datasets and analysis scripts are available from the corresponding author on reasonable request.

Declaration of competing interests

The author declares no competing interests.

Ethics approval

Not applicable. This study used only secondary, aggregated and publicly available data and did not involve human participants or animal experimentation.

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