INSTM Bulletin
Marine and Freshwater Sciences

Vol. 51, 2026, 111-137

Research Article

Sea surface-visible marine aquaculture in Tunisia: Mapping spatio-temporal distribution through satellite imagery and geospatial analysis (2004 - 2026)

Amel MZOUGHI * & **Mohamed Salah AZAZA**

University of Carthage. National Institute of Marine Sciences and Technologies (INSTM). Aquaculture Laboratory, 28 rue du 2 mars 1934, 2025 Salammbo, Tunisia

*Correspondence: amel.mzoughi@inat.u-carthage.tn

Received: 15/06/2026; **Accepted**: 05/08/2026; **Published**: 24/08/2026

Abstract: Offshore aquaculture is increasingly recognized as a strategic component of sustainable food systems and Blue Economy development; however, its long-term spatial dynamics remain poorly documented in many regions, particularly in North Africa. This study reconstructs the evolution of marine aquaculture concessions in Tunisia between 2004 and 2026 by integrating administrative concession records with multi-temporal satellite imagery.

A geospatial database was developed for 70 authorized sites, complemented by systematic interpretation of high-resolution historical imagery and Sentinel-2 data to map cage occupancy, infrastructure evolution, and spatial configuration. The results reveal a strong path-dependent development pattern, where early site allocation decisions largely determined long-term spatial persistence.

More than half of concessions remained active, while a significant proportion failed to reach sustained production, highlighting heterogeneity in site performance. Satellite-based reconstruction shows a marked expansion of finfish farming, alongside a progressive shift toward larger cages, standardized infrastructure, and more complex multi-line farm configurations.

Atlantic bluefin tuna fattening remained spatially restricted throughout the study period. A gradual offshore shift toward deeper waters was also observed.

Beyond methodological contributions, the resulting dataset provides a robust baseline for Marine Spatial Planning and Integrated Coastal Zone Management by distinguishing between authorized and effectively occupied sites (sites with visible aquaculture infrastructure), supporting evidence-based zoning and long-term coastal governance.

Keywords: Sustainable Aquaculture; Fish cages; Remote sensing; Geographic information systems; Spatio-temporal distribution; Marine spatial planning; Coastal zone management.

1. Introduction

Marine aquaculture has become one of the fastest-growing food production sectors worldwide and is increasingly recognized as a strategic component of the Blue Economy and sustainable food security agendas (FAO, 2024). As capture fisheries face increasing pressure from overexploitation, climate change, and habitat degradation, offshore aquaculture is being promoted as a means of expanding seafood production while reducing competition for coastal space and minimizing environmental conflicts in nearshore environments (Aguilar-Manjarrez et al., 2017; Gentry et al., 2017a).

Within this regional context, Tunisia has emerged as an important marine aquaculture producer in the central Mediterranean, reflecting the broader expansion of cage-based farming systems across the region.

Marine cage aquaculture in the Mediterranean Sea has expanded considerably during the last three decades, particularly through the development of farming systems for European seabass (*Dicentrarchus labrax*), gilthead seabream (*Sparus aurata*), and Atlantic bluefin tuna (*Thunnus thynnus*) fattening operations (Holmer, 2010; Cardia and Lovatelli, 2015).

This expansion has been accompanied by increasing attention to Marine Spatial Planning (MSP), Integrated Coastal Zone Management (ICZM), and ecosystem-based management approaches aimed at balancing aquaculture development with environmental conservation and competing maritime activities (Ehler and Douvere, 2009; European Commission, 2021).

Located in the central Mediterranean, Tunisia has developed a predominantly marine aquaculture sector based on cage farming of European seabass and gilthead seabream, together with bluefin tuna fattening activities.

In 2023, aquaculture production reached 20,483 tonnes, accounting for approximately 2.2% of total production in the Mediterranean and Black Sea region. Despite its relatively modest production volume at the regional scale, aquaculture contributed approximately 0.23% of Tunisia's National Gross Domestic Product (GDP), one of the highest contributions reported among Mediterranean countries (FAO, 2025).

Production is overwhelmingly dominated by finfish, reflecting the broader pattern observed across North Africa and western Asia (FAO, 2025). Despite the economic importance of the sector, knowledge regarding its long-term spatial evolution remains surprisingly limited. Existing information is generally restricted to annual production statistics and administrative reports, while little information is available concerning the spatial distribution of farms, infrastructure evolution, concession dynamics, site persistence, or historical patterns of occupation.

This lack of spatially explicit information constitutes a significant limitation for marine spatial planning, environmental assessment, carrying-capacity studies, and future aquaculture zoning initiatives. Understanding where farms have been established, how they have evolved through time, and which sites have remained active or been abandoned is essential for evaluating sector performance and supporting evidence-based coastal management decisions (Kapetsky et al., 2013; Aguilar-Manjarrez et al., 2017).

Recent advances in Earth Observation technologies have significantly improved the ability to monitor aquaculture infrastructure at regional and global scales. High-resolution imagery and Sentinel-2 satellite data have been successfully used to identify aquaculture cages, estimate infrastructure expansion, monitor farm occupancy, and assess spatial development trajectories in several regions worldwide (Ottinger et al., 2017). However, such approaches have rarely been applied in North Africa, and, to date, no comprehensive reconstruction of marine aquaculture concessions development exists for Tunisia.

To address this knowledge gap, this study integrates administrative records and multi-temporal satellite imagery to reconstruct the spatio-temporal evolution of marine aquaculture concessions along the Tunisian coast between 2004 and 2026. It examines concession dynamics, site persistence, and infrastructure development, providing the first national-scale assessment of marine aquaculture concession evolution in Tunisia and a baseline for MSP, ICZM, aquaculture zoning, and sustainable coastal governance.

2. Materials and Methods

The approach integrates administrative records with multi-temporal remote sensing analysis, combining historical imagery and Sentinel-2 data to reconstruct the spatial and temporal evolution of marine aquafarms.

These two core datasets are then integrated with environmental spatial layers, including bathymetry, marine protected areas, and coastal infrastructure, to enable a comprehensive spatiotemporal assessment of aquaculture development along the Tunisian coast.

The overall methodological framework adopted in this study is summarized in Figure 1. For the purposes of this study, the term "marine aquaculture concession" refers to an administratively authorized area allocated for marine aquaculture activities in open coastal waters.

Concessions located within lagoons, lakes, or other transitional water bodies were excluded from the analysis. Similarly, land-based aquaculture facilities situated along the coastline were not considered. Each administratively authorized area was treated as an independent spatial unit. Consequently, concession extensions were considered separate sites whenever they corresponded to a newly authorized area with distinct spatial boundaries. Although extension areas often encompass part or all the original concession, they were retained as separate records in the inventory because they represent different authorized spatial footprints and management units over time.

2.1 Administrative inventory

An administrative investigation was conducted to establish an inventory of marine aquaculture projects authorized along the Tunisian coast between 2004 and 2026. Although the satellite-based analysis covers (2004-2026), the administrative database includes concessions granted from 1998 onwards, as the first sea-based marine aquaculture concessions in Tunisia predate the availability of suitable satellite imagery.

These earlier administrative records were retained to reconstruct the complete historical evolution of the sector, whereas the spatial reconstruction derived from satellite observations begins in 2004.

Information was collected from administrative records, technical reports, project documentation, and institutional archives, complemented by interviews with technicians and staff involved in project management and monitoring.

For each project, available administrative, technical, production, and spatial information was compiled into a geodatabase.

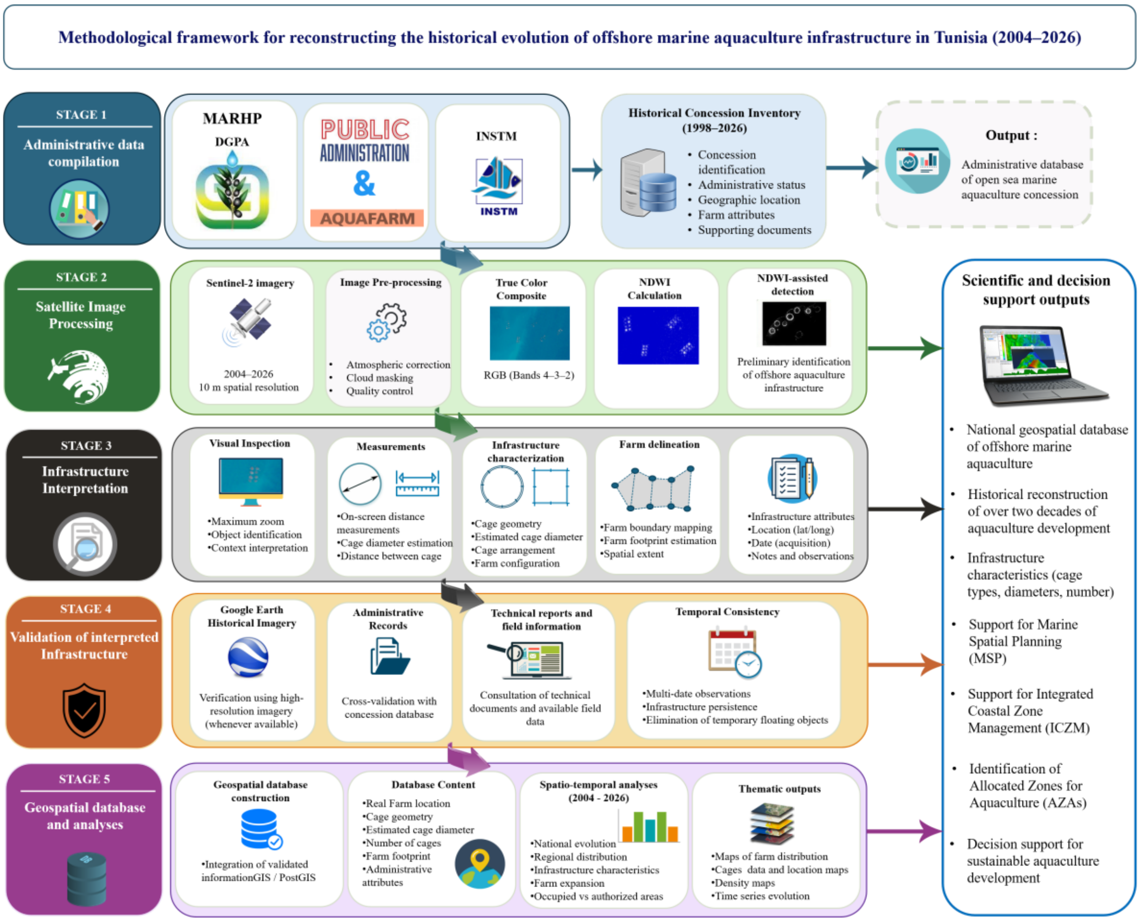


Figure 1. The methodological framework developed for reconstructing the historical evolution of sea-based marine aquaculture in Tunisia between 2004 and 2026. The workflow integrates administrative concession records, multi-temporal Sentinel-2 imagery, NDWI-assisted detection, manual interpretation, multi-source validation using Google Earth imagery and administrative information, and geospatial database construction to support spatial analyses and marine spatial planning.

The variables collected are summarized in Table 1. as a reference for subsequent comparison with aquaculture cage locations identified through satellite imagery.

2.2 Satellite-based assessment of aquaculture cage occupancy

2.2.1. <u>Data sources and temporal coverage</u>

The spatial distribution of marine aquaculture cages was reconstructed using historical high-resolution imagery and Sentinel-2 multispectral data.

This multi-source, multi-temporal approach is widely used in aquaculture monitoring to ensure long-term spatial continuity and improve detection robustness across heterogeneous datasets (Fu et al., 2019; Wang et al., 2019; Xia et al., 2026).

Historical imagery available through Google Earth and similar archives was used to identify aquaculture installations for the period 2004-2014. Such high-resolution imagery is commonly applied for manual or semi-automated extraction of aquaculture structures due to its ability to resolve small floating features and cage geometries (Fu et al., 2019; Wang et al., 2019).

For the period 2015 to May 2026, Sentinel-2 Level-1C and Level-2A imagery were used to monitor cage occupancy.

Sentinel-based monitoring has been extensively validated for aquaculture mapping due to its adequate spatial resolution and temporal revisit capacity, particularly when combined with multi-temporal compositing strategies (Wang et al., 2018; Xia et al., 2026).

Table 1. Administrative inventory and geodatabase development of authorized marine aquaculture project.

Category	Main variables	Description	Data sources (type of records)
Administrative	Project ID, concession number, operator name, licensing status, approval dates, production capacity	Legal and institutional identification of each aquaculture project	Administrative records, Ministry files, licensing documents
Spatial	Coordinates (X, Y), site boundaries,	Geolocation of aquaculture sites	GIS layers, nautical charts, institutional spatial archives
Technical	Cage type, number of cages, cage diameter, installation depth	Physical and engineering characteristics of farming systems	Technical reports, project design documents, field reports
Production	Species farmed, stocking density, production volume, harvest cycles	Operational aquaculture performance indicators	Production reports, company records, monitoring reports
Temporal	Year of installation, operational period, status evolution	Temporal evolution of each aquaculture site	Historical archives, administrative records
Socio-economic	Employment, investment cost, ownership structure	Economic and social dimensions of projects	Institutional reports, project documentation, surveys

To ensure temporal consistency, one representative image with minimal cloud cover was selected for each month.
This multi-temporal selection strategy reduces atmospheric bias and improves the reliability of temporal change detection in coastal aquaculture environments (Xia et al., 2026).

The inventory includes all projects that received official authorization during the study period, regardless of their current operational status.

2.2.2. Image processing and water masking

All Sentinel-2 images were harmonized to a spatial resolution of 10 m and visually inspected prior to analysis to ensure radiometric consistency. Pre-processing steps such as harmonization and quality filtering are essential in multi-temporal aquaculture mapping workflows to reduce classification uncertainty (Wang et al., 2018; Xia et al., 2026).

To isolate aquatic environments, the Normalized Difference Water Index (NDWI) was calculated using the green (Band 3) and near-infrared (Band 8) bands:

$$\boldsymbol{NDWI} = \frac{B3 - B8}{B3 + B8} \quad \text{Equation 1.}$$

NDWI-based water masking is a standard and widely validated technique for separating land-water interfaces and improving the identification of floating aquaculture infrastructure (Wang et al., 2018). The resulting water mask was used to exclude terrestrial areas and improve the contrast of aquaculture structures located on the water surface.

2.2.3. NDWI-based detection, verification and characterization of aquaculture infrastructure

The resulting NDWI-based classification was used to identify potential sea-based aquaculture installations by highlighting floating structures visible on the sea surface. All detected aquaculture installations were then manually verified using the Sentinel-2 True Color composite (RGB: Bands 4-3-2) available through the Copernicus Browser.

The interactive visualization tools, including high-zoom inspection and on-screen distance measurements, were used to visually confirm the presence of cages, characterize their geometry, estimate cage diameter, determine cage arrangement, and verify the spatial extent of each farm.

This manual verification was systematically applied to all aquaculture sites included in the database.

Whenever historical very-high-resolution imagery was available through Google Earth, an additional independent verification was performed. Cage diameters, farm layouts, and infrastructure configurations observed in Sentinel-2 imagery were compared with the higher-resolution imagery, allowing confirmation of measurements and interpretation whenever temporal correspondence between image acquisitions was available.

Manual interpretation was preferred because the spatial resolution of Sentinel-2 imagery does not consistently resolve individual cage boundaries, particularly where cages are closely spaced or partially submerged. The interpretation workflow therefore combined spectral information derived from NDWI with detailed visual interpretation and multi-source validation. Rather than relying exclusively on automated pixel classification, the final database was established through interpretation supported by repeated observations from multiple image sources and administrative records.

2.2.4. Validation of aquaculture infrastructure interpretation

The reliability of the interpreted aquaculture infrastructure was assessed through a qualitative multi-source validation procedure integrating historical Google Earth imagery when available, administrative concession records, and available technical documentation describing farm characteristics.

Particular attention was paid to farm geometry. Circular and square cage systems were readily distinguishable through visual interpretation because of their contrasting geometric signatures, allowing reliable classification of cage shape throughout the study period.

Although Sentinel-2 imagery does not provide engineering-level precision for direct measurement of individual cages, the combination of NDWI extraction, manual interpretation, on-screen measurements, very-high-resolution imagery, and administrative validation substantially increased confidence in the reconstructed aquaculture database.

2.2.5. Cage detection and spatial mapping

Verified aquaculture installations were digitized to create the historical geospatial database (Figure 2). Digitization was based on the interpretation of persistent floating infrastructure exhibiting characteristic geometric patterns, spatial clustering, and temporal consistency across successive observations.

This semi-manual workflow combines automated spectral extraction with visual interpretation and remains a robust approach for identifying aquaculture structures when automated classification is limited by spectral similarity with surrounding features (Fu et al., 2019; Wang et al., 2019).

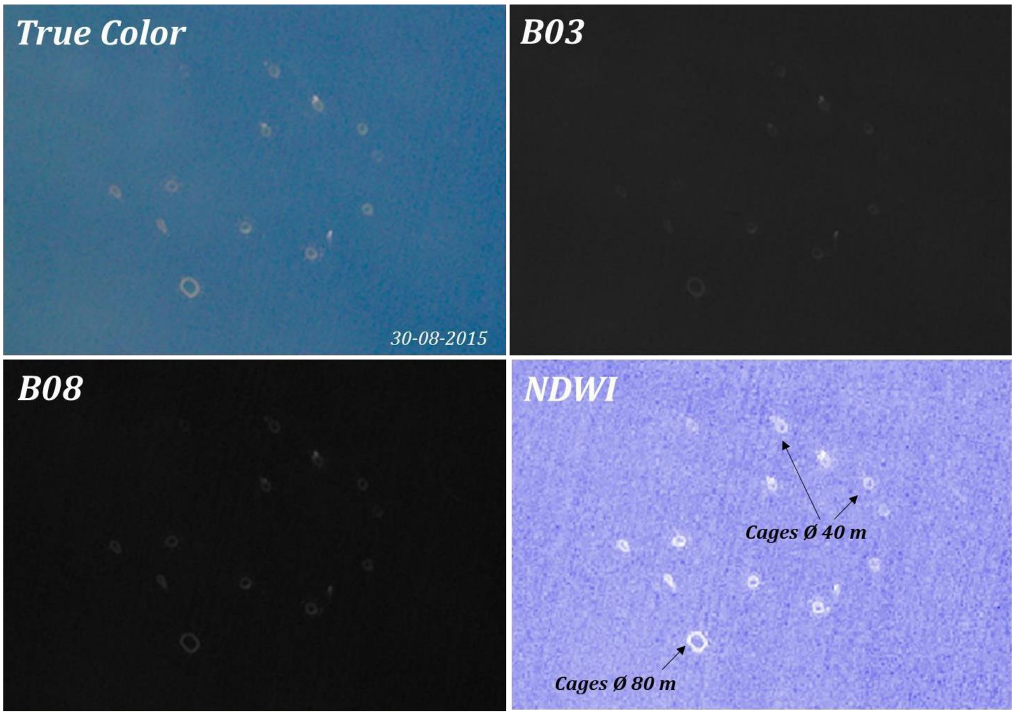
These morphological and temporal criteria are commonly used in both machine learning and object-based aquaculture mapping frameworks to distinguish cages from natural or anthropogenic floating objects (Fu et al., 2019; Choung and Jo, 2020; Sui et al., 2020).

Temporal persistence across consecutive observations was used to distinguish aquaculture facilities from transient objects such as vessels or temporary surface features. Similar persistence-based logic has been successfully applied in previous studies to improve the reliability of floating aquaculture detection (Priyanto et al., 2020; Xia et al., 2026).

The reported diameter classes in this study should be interpreted as reconstructed infrastructure attributes rather than engineering-grade field measurements.

2.3. Geospatial datasets and environmental spatial layers

Three additional spatial layers were integrated to enrich the geospatial analysis (Table 2.). Bathymetric information was derived from the GEBCO gridded global bathymetry dataset (GEBCO Compilation Group, 2024), used to extract water depth values at the locations of detected aquaculture cages. This enabled the characterization of the bathymetric distribution of studied farms across the study period.



Note: *The cages identified in the satellite imagery were provisionally classified as 40 m diameter cages based on the apparent cage stretching and spatial dimensions observed in the images. However, some installations may potentially correspond to 50 m cages. Due to the available image resolution, the 40 m classification was retained as a first interpretation pending validation through farm-level verification or more reliable technical sources.*

Figure 2. Configuration of floating bluefin tuna fattening cages in the Gulf of Hammamet (Tunisia) derived from high-resolution Sentinel imagery (UTM 32N, EPSG:32632; 8 m spatial resolution) using True Color composites, Band 3, Band 8, and NDWI analysis.

Table 2. Sentinel imagery Source and supporting geospatial datasets for bathymetric, environmental, and infrastructure analysis.

Dataset	Type	Purpose in Study	Source
Copernicus Dataspace Browser imagery	Satellite optical imagery	Support detection and validation of aquaculture cages and spatial configuration analysis	https://browser.dataspace.copernicus.eu *Format/Resolution: TIFF (32-bit float), 194 × 154 px, ~8 m/pixel, UTM 32N (EPSG:32632)*
GEBCO Gridded Bathymetry (GeoTIFF)	Raster (bathymetry)	Extraction of water depth at cage locations and bathymetric analysis of farm distribution	https://download.gebco.net/
MAPAMED	Vector (MPAs)	Assessment of spatial interaction between aquaculture sites and Marine Protected Areas	https://www.mapamed.org/
APIP Tunisia	Port & coastal infrastructure data	Identification of ports and coastal service infrastructure relevant to aquaculture logistics and site accessibility	https://www.apip.nat.tn/b

Furthermore, spatial data on Marine Protected Areas (MPAs) were obtained from the MAPAMED database under the EU Horizon Europe mission “Restore our Ocean and Waters” (European Commission, 2024), allowing the assessment of spatial overlaps between aquaculture sites and environmentally protected zones.

Finally, ports and coastal infrastructure information was obtained from the Tunisian Fishing Ports and Facilities Agency (APIP-Agence des Ports et des Installations de Pêche), supporting the identification of proximity relationships between aquaculture sites and maritime service hubs.

3. Results

The integration of administrative records and satellite observations enabled the reconstruction of both the institutional development and the physical occupation of marine aquaculture sites along the Tunisian coast (2004-2026). The results provide the first comprehensive overview of concession allocation dynamics, farm establishment, infrastructure evolution and spatial occupation patterns at the national scale.

3.1. Historical reconstruction of marine aquaculture concessions (2004 - 2026)

3.1.1. Evolution of site allocation through time

The administrative inventory identified 70 sea-based marine aquaculture concessions allocated between 1998 and 2026. Although the satellite-based reconstruction presented in this study covers the period 2004-2026, earlier concessions were retained to reconstruct the complete administrative history of the Tunisian sea-based marine aquaculture sector. (Figure 3 and Figure a-d in Appendix I.).

Finfish aquaculture overwhelmingly dominates the sector, accounting for 78.6% of all concessions, whereas shellfish farming and bluefin tuna fattening represent 11.4% and 10.0%, respectively. This distribution reflects the strong orientation of Tunisian marine aquaculture toward marine finfish production, which remains the principal farming activity in open coastal waters (Figure 3).

The spatial distribution of concessions is highly concentrated within the Gulf of Hammamet (Nabeul to Mahdia), which hosts 80.0% of the inventoried concessions (56 projects). In contrast, Northern Tunisia and the Gulf of Gabès account for only 11.4% and 8.6% of the total concessions, respectively (Figure 3).

This marked geographical concentration highlights the Gulf of Hammamet as the primary hub for marine aquaculture development in Tunisia.

Concession allocation was highly uneven through time, with a major development phase during the 2010s. The year 2010 represented the main allocation peak, accounting for 24.2% of all concessions (n = 16), followed by a secondary peak in 2015 (10.6%; n = 7) (Figure 4).

By 2018, more than 70% of all concessions had already been allocated. These results (Figure 4) indicate an initial expansion phase followed by a more gradual and intermittent allocation process, suggesting a transition from exploratory development toward a more mature planning stage.

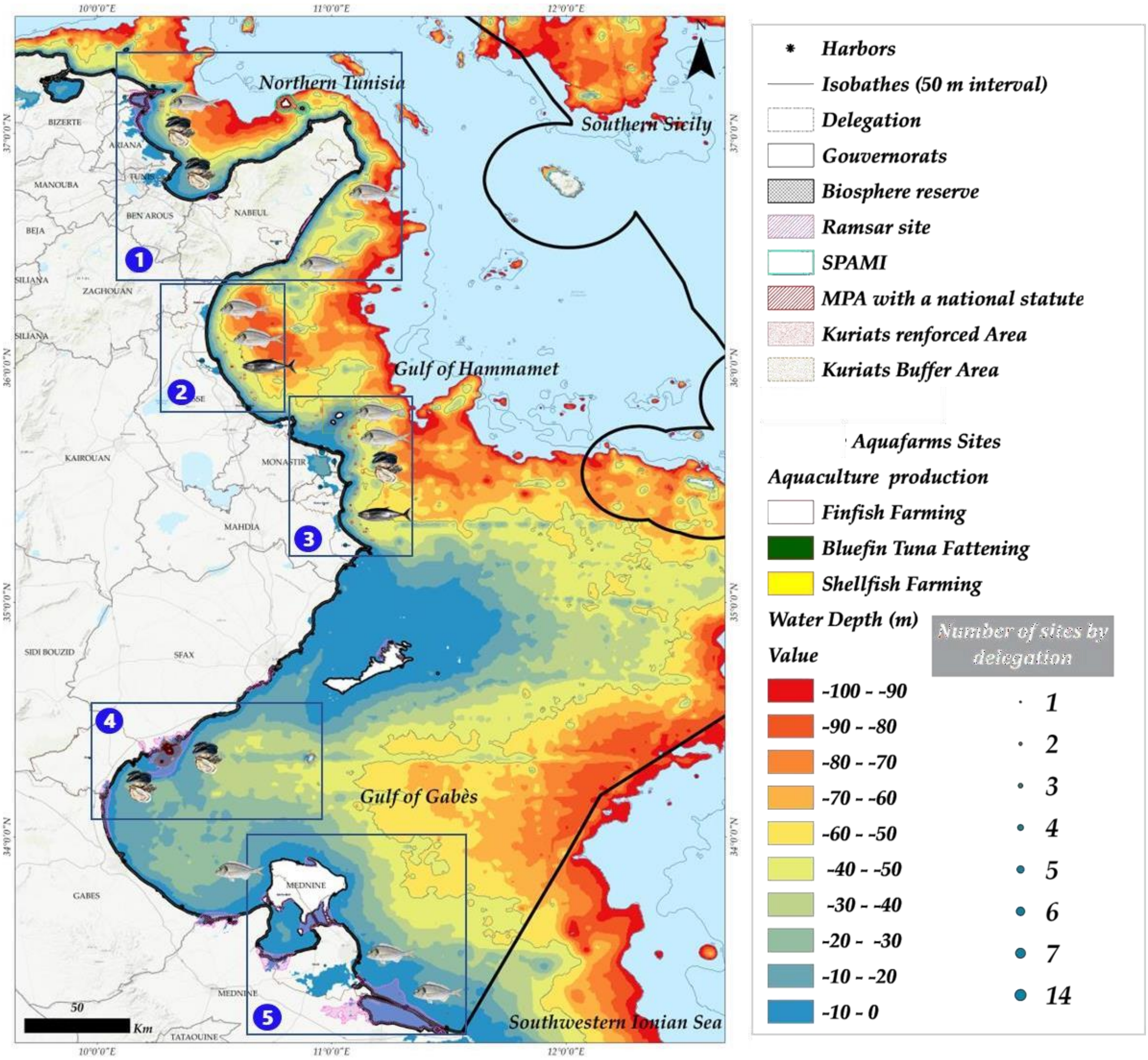


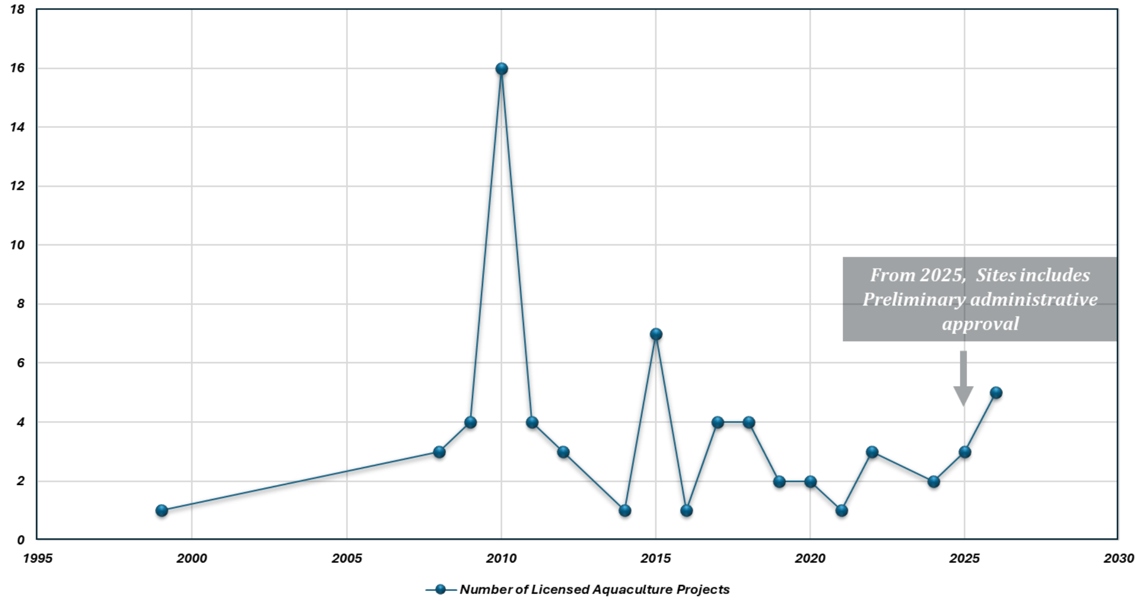
Figure 3. Spatial distribution of marine aquaculture concessions (open sea sites) in Tunisia (2004-2026) with bathymetry, protected areas, and administrative delegation classification, with zoomed areas (1-5) presented in Figures a-e (Appendix I).

3.1.2. Administrative and operational status of concessions

Among the identified sites, 51.4% were classified as active, while 25.7% were closed and 10.0% inactive.

Preliminary administrative approvals represented 7.1%, whereas relocated (1.4%) and reactivated sites (4.5 %) accounted for only a small proportion of the total inventory.

Approximately 70% of concessions reached a production phase, while nearly one-third failed to achieve sustained operational activity. Most concessions (82.9%) remained under their original authorization status, indicating limited administrative restructuring after allocation.



The sites considered include only administratively licensed marine aquaculture projects located in open-sea environments (nearshore/offshore farming systems). From 2025 onwards, the database was expanded to include Shellfish sites that have obtained a Preliminary administrative approval, as well as extension projects associated with existing active farms that have received a principal agreement for either capacity expansion or the establishment of a new farming site.

Figure 4. Annual trend in the number of licensed sea-based marine aquaculture projects in Tunisia (finfish, bluefin tuna fattening and shellfish aquaculture outside lagoons and land-based systems excluded) up to 2026.

3.1.3. Ownership and Production system

The sector was characterized by a strong predominance of male ownership (92.9%). Circular floating cages represented the dominant production technology, accounting for many active and historical sites, whereas submersible cages and alternative systems (square cage) remained limited (Figure 5).

3.1.4. Concession Lifecycle Trajectories

Analysis of concession trajectories revealed that most sites followed relatively simple development pathways. Initial active concessions represented the largest category, indicating that many projects entered production without major administrative modification. In contrast, a substantial proportion of concessions became inactive or closed after allocation, highlighting the occurrence of project discontinuation within the sector.

Relocation, reactivation, and extension processes remained relatively uncommon, suggesting that adaptive spatial reconfiguration has played a limited role in the historical development of sea-based aquaculture in Tunisia.

Overall, the results indicate that the long-term fate of most projects was strongly influenced by their initial allocation and implementation phase.

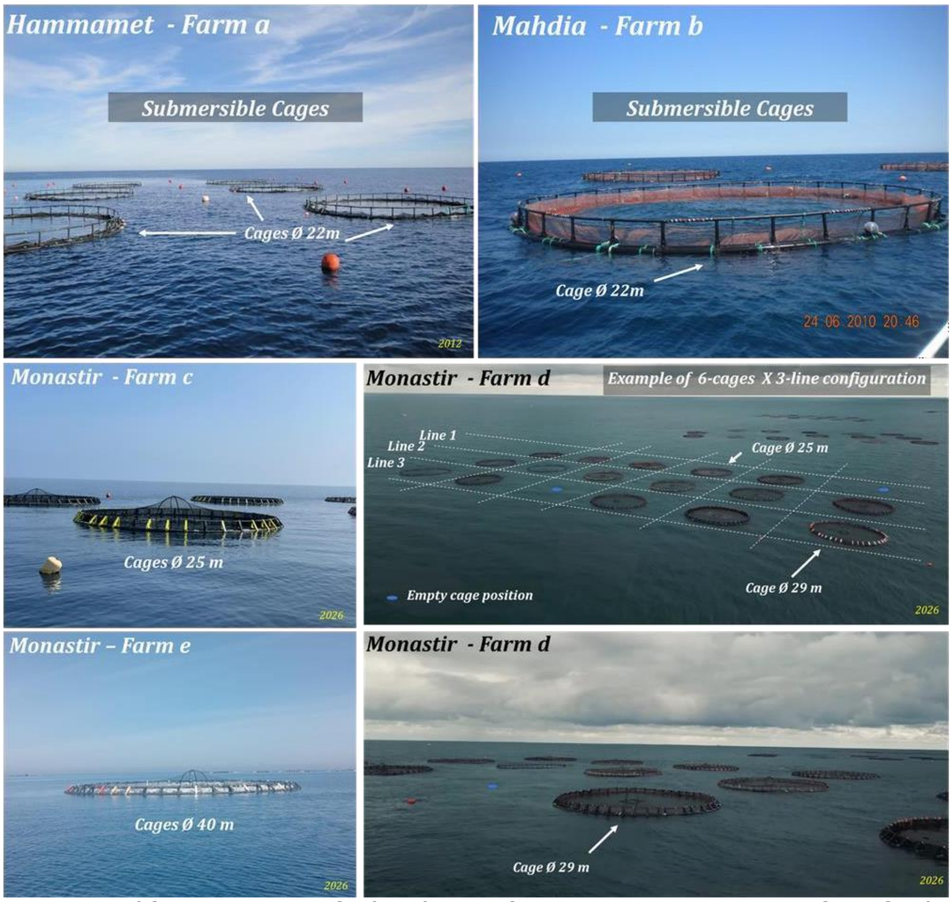


Figure 5. Examples of Submersible and Surface floating Cage systems and Multi-Line Cage Configurations observed in Tunisian Aquaculture Far.

Overall, the administrative reconstruction reveals a sector characterized by strong dependence on initial allocation decisions, moderate project attrition, and limited relocation dynamics.

3.2 Spatio-temporal evolution of sea-based marine aquaculture occupation (2004 - 2026)

3.2.1. <u>Evolution of evolution of productive farming sites</u>

Satellite observations revealed a progressive expansion of marine aquaculture along the Tunisian coast. Finfish farming increased from a single detected site in 2004 to 24-28 active sites annually after 2015, reaching a maximum of 28 sites in 2020 (Figure 6).

In contrast, bluefin tuna fattening remained spatially restricted throughout the study period, with only two to four active sites observed annually (Figure 6).

The expansion of Tunisian sea-based aquaculture was therefore primarily driven by finfish farming rather than bluefin tuna fattening activities.

3.2.2. <u>Evolution of cage numbers and infrastructure</u>

The number of cages increased from 72 units in 2004 to 247 in 2014. Following the availability of continuous satellite coverage after 2015, annual inventories ranged between 578 and 764 cages (Figure 7).

Finfish farming represented 95-98% of all cages, whereas bluefin tuna fattening accounted for only 2-6% of the national inventory (Figure 7).

A progressive standardization of infrastructure was observed. The proportion of 25 m cages increased from 36.8% in 2015 to 71.6% in 2026, becoming the dominant production unit (Figure 7).

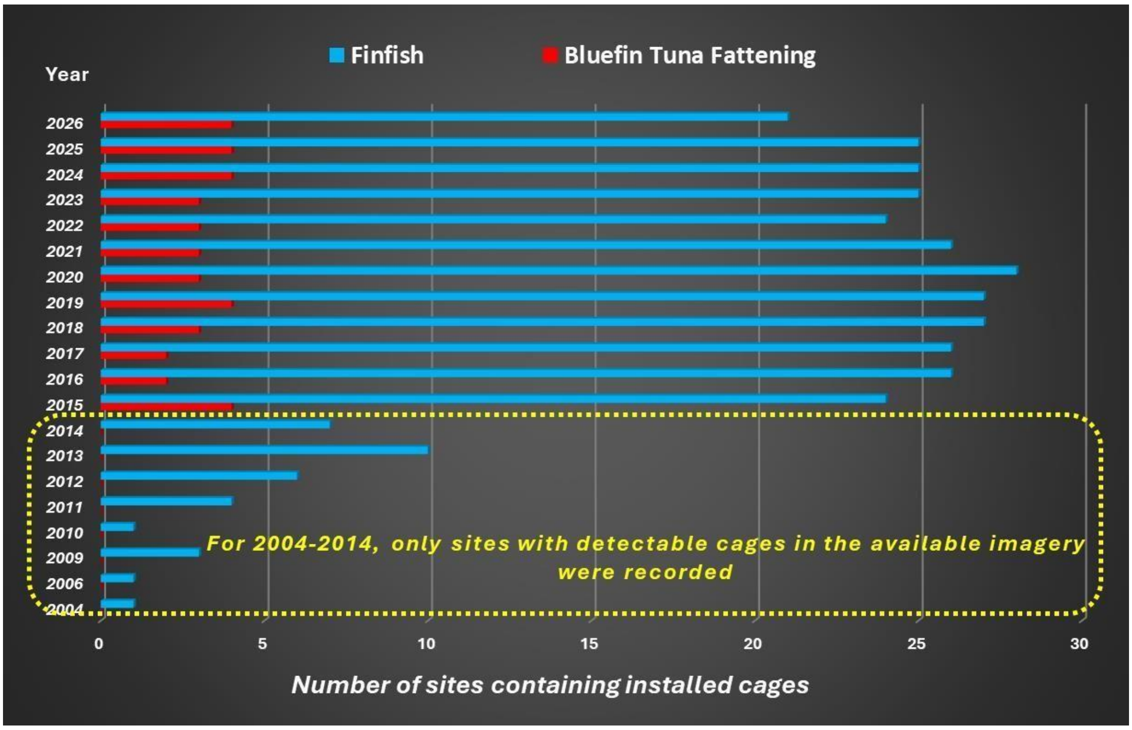


Figure 6. Temporal evolution of finfish farming and blue tuna fattening occupied aquaculture sites identified from satellite imagery along the Tunisian coast (2004-2026).

Conversely, smaller cages progressively disappeared, and the importance of 22 m cages declined substantially.

Bluefin tuna fattening remained highly standardized throughout the study period and relied almost exclusively on large circular cages ranging between 40 and 50 m in diameter (Figure 7).

3.2.3. <u>Evolution of farm Spatial configuration</u>

The spatial organization of farms evolved from simple single-line arrangements during the early development phase toward increasingly complex double-line and triple-line configurations (Figure 8).

Between 2011 and 2021, two-line arrangements composed of approximately 12 cages became the dominant farm layout (Figure 8).

After 2021, larger multi-line systems containing 18 to 21 cages became increasingly frequent, reflecting growing production intensity and farm-scale consolidation (Figure 8).

Bluefin tuna fattening farms exhibited a simpler spatial organization. Most bluefin tuna cages were arranged as isolated units or within one- or two-line configurations (Figure 9).

No triple-line bluefin tuna configurations were detected during the study period.

The number of bluefin tuna batches remained low, generally ranging from one to three groups annually, reflecting the limited number of bluefin tuna fattening operations in Tunisia compared with finfish farming.

This evolution demonstrates a progressive transition from relatively small floating installations toward more industrialized farming configurations.

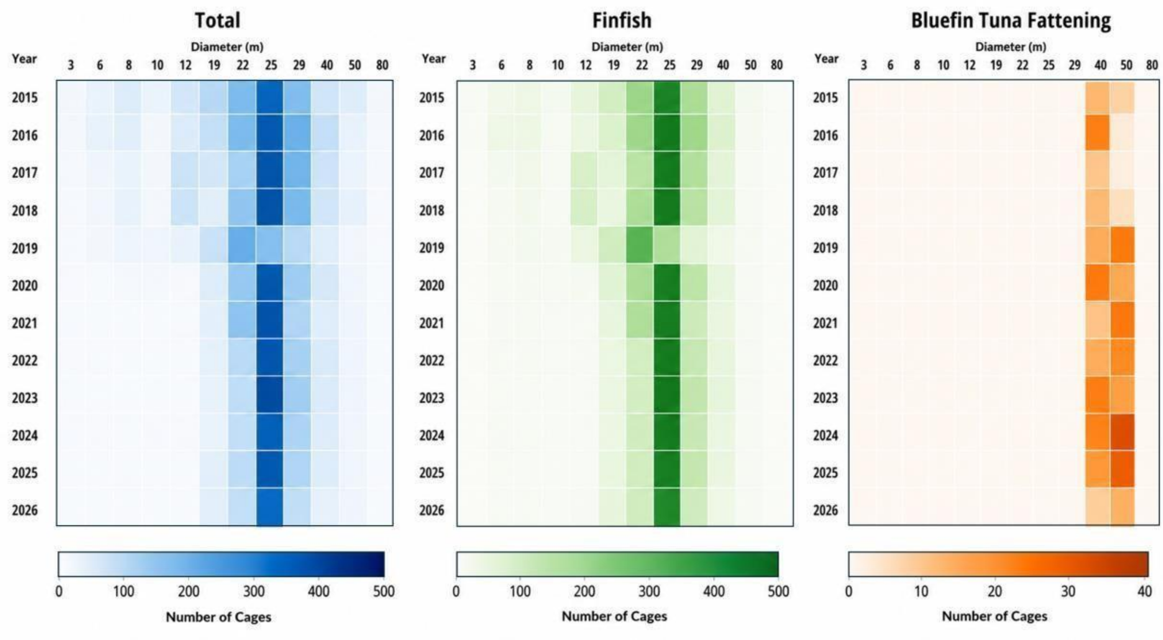


Figure 7. Heatmaps of annual cage distribution by aquaculture type (total, finfish and bluefin tuna fattening) and cage diameter in Tunisia (2004-2026).

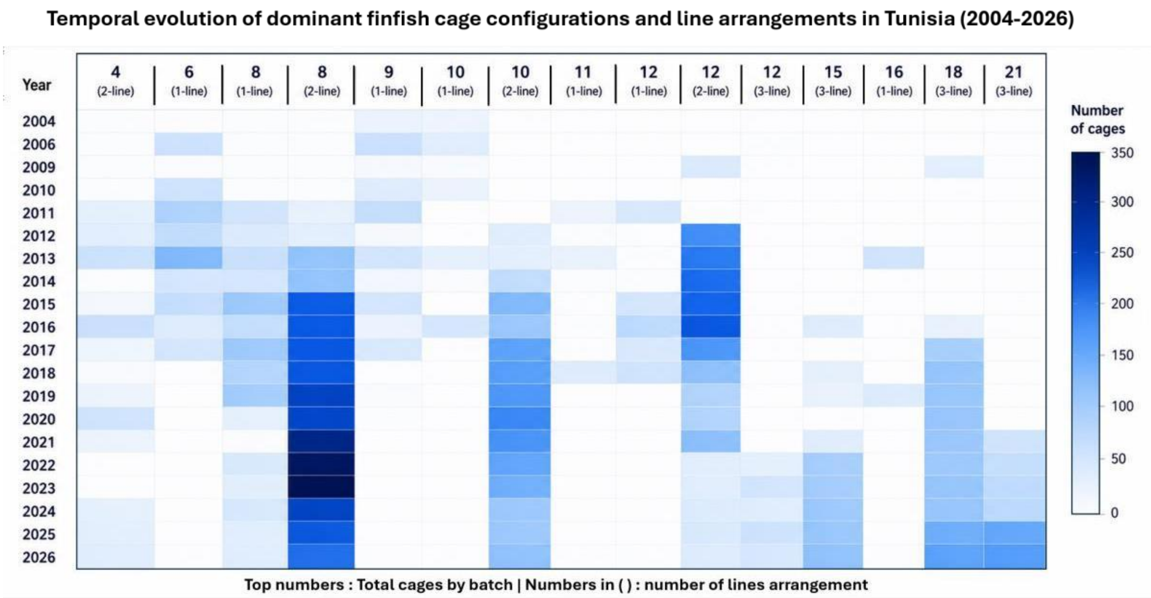


Figure 8. Temporal evolution of dominant Finfish cage configurations and line arrangements in Tunisia (2004-2026).

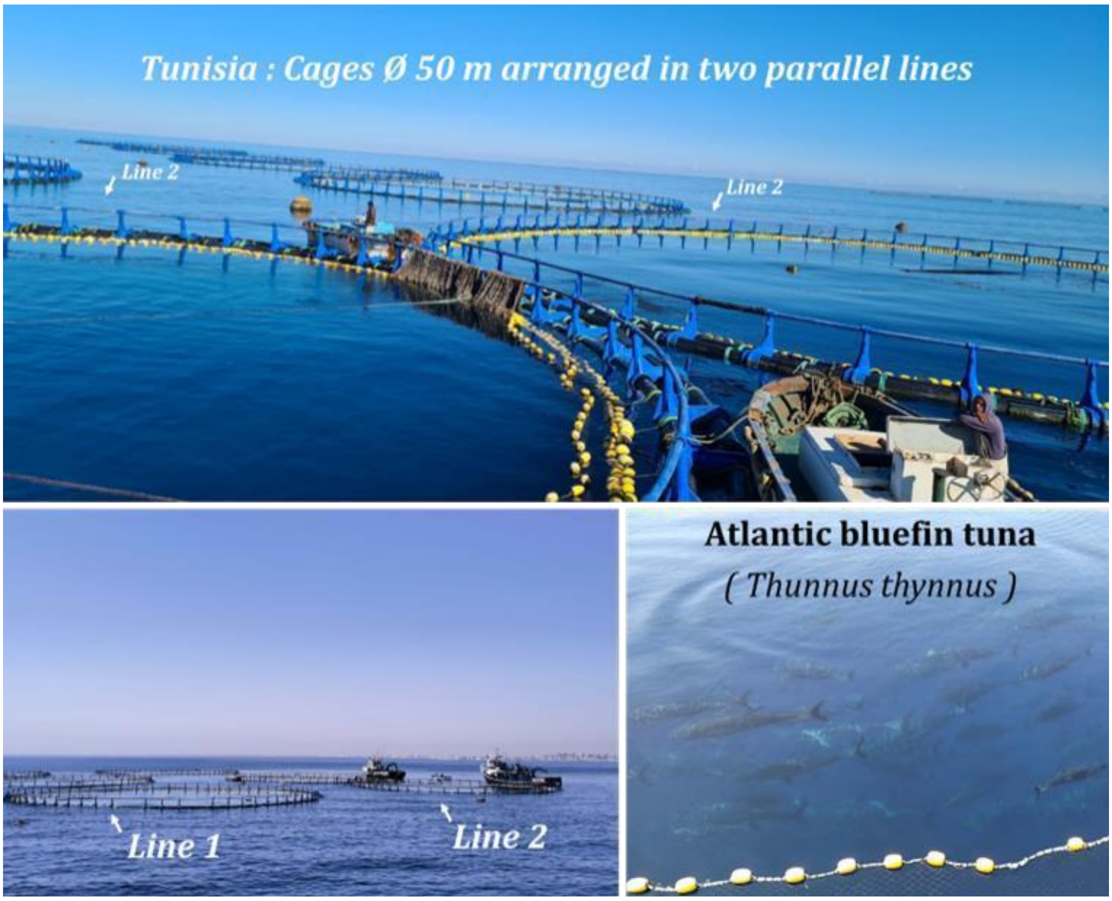


Figure 9. Example of Parallel Double-Line Configuration in an open sea bluefin tuna fattening Farm in Tunisia.

3.3 Spatial distribution and offshore expansion

3.3.1 Bathymetric distribution

Finfish farms were distributed across a broad depth range but were primarily concentrated between 20 and 40 m depth (Figure 1 and Figure a-e Appendix I). bluefin tuna fattening exhibited a much narrower bathymetric niche, with approximately 96% of sites located between 30 and 40 m depth (Figure 1 and Figure a-d Appendix I).

Comparison between historical and recent observations revealed a gradual offshore shift in finfish farming. Between 2015 and 2026, the proportion of cages installed between 30 and 40 m depth increased, while installations in waters shallower than 20 m decreased substantially. Simultaneously, occupation of the 40-50 m depth class increased, indicating progressive movement toward deeper offshore environments.

3.4. Spatial singularities and atypical aquaculture systems

Several atypical aquaculture configurations were identified through satellite analysis.

A unique farm operating within the Bhirat El Bibane area (a Ramsar Site) combined circular and square cages installed in shallow waters and represented the only observed example of mixed cage geometry in Tunisia (Figure 10). The site operated within an ecologically sensitive environment and near traditional fixed fisheries (Figure 10).

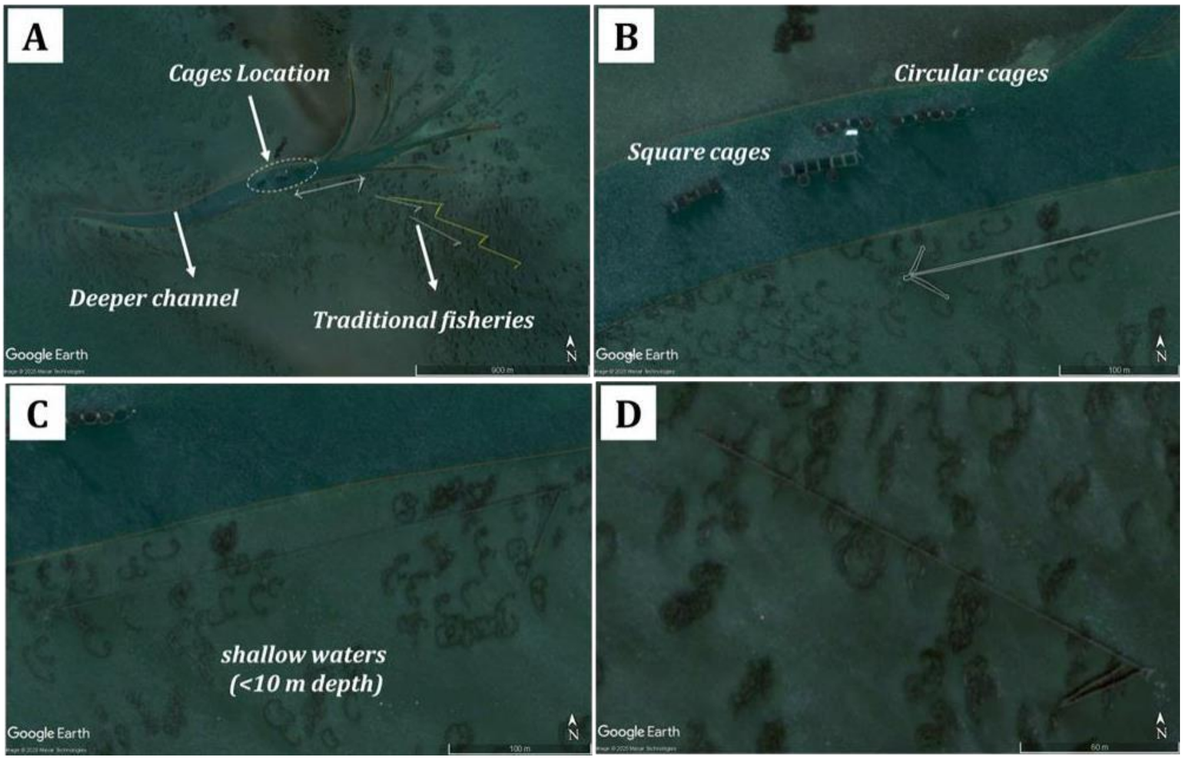


Figure 10. Shallow-Water floating Cage Farming, Mixed Cage Geometry, and Traditional Fixed Fisheries in Southern Tunisia.

Additional atypical farms were identified within the Port of Zarzis (Figure 11), where cage systems operated inside the port basin rather than in exposed open-sea conditions. These farms used small-diameter cages (<12 m), a configuration not observed elsewhere along the Tunisian coast (Figure 11).

The analysis also identified the only automatic sea-based floating feeding barge detected in Tunisia (Figure 12), located in the Gulf of Hammamet and continuously associated with the same farm from 2011 to 2026.

These singular cases highlight the diversity of farming strategies that have existed within the Tunisian aquaculture sector and demonstrate the capacity of remote sensing approaches to identify unconventional infrastructure and occupation patterns.

3.5 Comparison between administrative allocations and observed occupation

The comparison between concession records and satellite-derived observations revealed that authorized sites and occupied sites do not always coincide.

While concession allocation increased rapidly during the 2000s and 2010s, a significant proportion of allocated sites did not result in long-term occupation or sustained production activity.

The combined use of administrative and satellite datasets therefore provides complementary perspectives on sector development, allowing the distinction between planned aquaculture expansion and actual spatial occupation of the coastal zone.

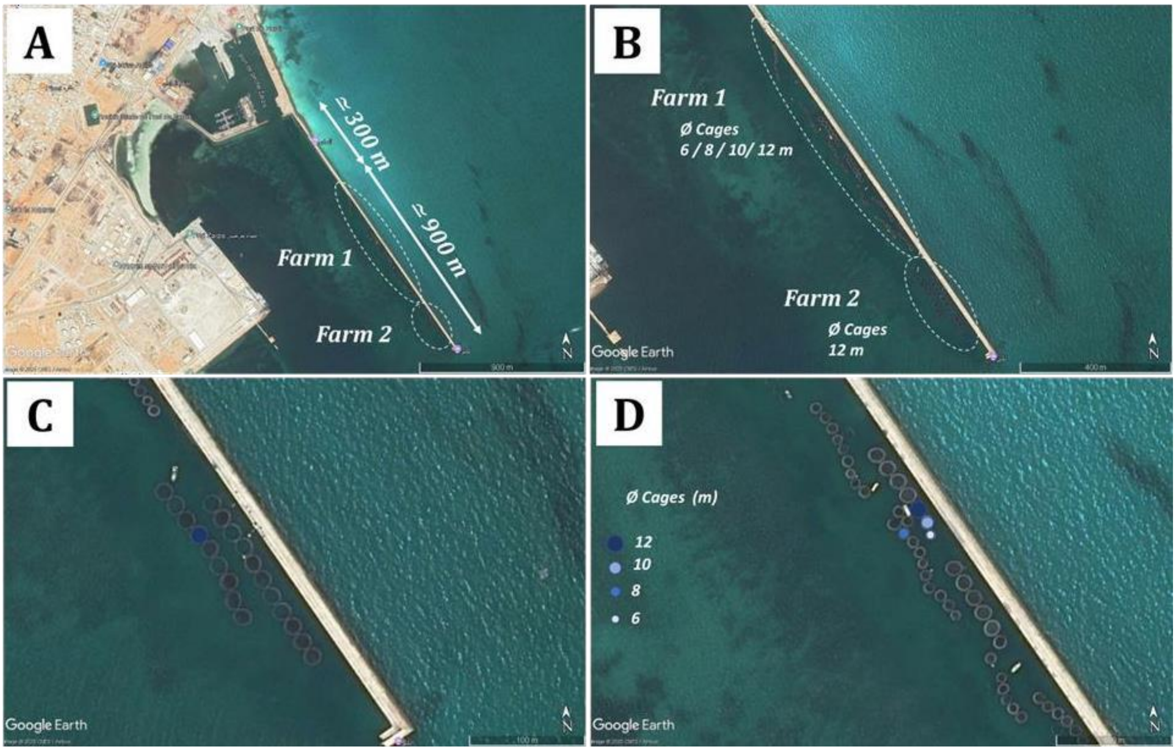


Figure 11. Example of marine aquaculture installations within the Port of Zarzis, showing small-diameter cages (<12 m) deployed inside the port basin rather than in offshore waters.

Figure 12. Automatic sea-based floating feeding barge associated with a finfish farming site in the Gulf of Hammamet, representing the only such infrastructure identified in Tunisia during the study period.

4. Discussion

The present study provides the first national-scale reconstruction of the spatial and structural evolution of sea-based marine aquaculture in Tunisia over more than two decades by integrating historical satellite imagery with administrative concession records. Beyond documenting historical changes, this approach offers new insights into the long-term development of the sector, revealing patterns of farm persistence, infrastructure modernization, and offshore expansion that are not captured by conventional spatial inventories.

These findings contribute to a better understanding of how sea-based marine aquaculture has evolved in response to environmental suitability, technological progress, and management practices, while highlighting the value of historical Earth Observation data as an evidence base for sustainable aquaculture planning.

4.1. Historical evolution, spatial concentration, and persistence of sea-based marine aquaculture

The Sea-based marine aquaculture in Tunisia exhibits a marked spatial concentration, with approximately 80% of concessions located within the Gulf of Hammamet (Figure 3).

This pronounced clustering indicates that sector development has been strongly influenced by the coexistence of favorable environmental conditions and operational advantages rather than occurring uniformly along the coastline.

Suitable bathymetry, hydrodynamic conditions, accessibility to port infrastructure, and proximity to markets are recognized as major drivers of aquaculture site selection and frequently result in the concentration of farming activities within the most suitable coastal areas (Ross et al., 1993; Aguilar-Manjarrez et al., 2017; Falconer et al., 2020). Similar spatial clustering has been reported in other Mediterranean and international aquaculture regions, where production progressively converges towards locations offering the best balance between environmental suitability, operational efficiency, and economic viability (Gentry et al., 2017a; Lester et al., 2018).

Despite the strong spatial concentration observed in the Gulf of Hammamet, a limited number of atypical farming systems were identified in other coastal environments (Figure 10 and 11). These isolated cases illustrate the capacity of the sector to adapt production strategies to local environmental and operational conditions, while reinforcing that the overall spatial organization remains dominated by a relatively small number of highly suitable farming areas.

The temporal evolution of concession allocation further suggests a progressive transition in the development of the Tunisian aquaculture sector (Figure 4). After a period of rapid expansion during the 2000s and early 2010s, the limited number of new concessions allocated after 2018 indicates that the sector has entered a more mature planning phase (Figure 4 and 6).

Rather than reflecting a slowdown in development, this stabilization suggests that the most suitable farming areas had largely been identified, with subsequent growth increasingly relying on the optimization and modernization of existing concessions instead of continuous spatial expansion. Similar development trajectories have been observed in mature aquaculture industries, where initial geographical expansion is gradually replaced by production intensification and more strategic spatial planning (Gentry et al., 2017b; Lester et al., 2018; FAO, 2024).

This interpretation is supported by the long-term persistence of productive farming sites observed throughout the study period. Most active farms remained within their original concession boundaries despite substantial changes in production infrastructure, indicating that the initial site-selection process successfully identified locations capable of supporting sustained aquaculture production. Previous studies have consistently demonstrated that environmental suitability, hydrodynamic conditions, operational accessibility, and economic feasibility are fundamental determinants of long-term farm performance (Ross et al., 1993; Aguilar-Manjarrez et al., 2017; Falconer et al., 2020). Furthermore, the considerable investment required for offshore infrastructure, including cages, mooring systems, and associated logistics, provides a strong incentive to maintain production within proven farming areas rather than relocate to new sites (Di Trapani et al., 2014; Chu et al., 2020).

Conversely, the inactive and abandoned concessions identified in this study demonstrate that administrative licensing alone does not guarantee successful aquaculture development.

The discrepancy between authorized concessions and effective farm occupation highlights the importance of integrating environmental suitability with technical, economic, and governance considerations throughout the planning process.

Historical information on both successful and unsuccessful farming sites therefore represents an important source of evidence for improving future concession allocation and reducing planning uncertainty (Hovik and Stokke, 2007; Aguilar-Manjarrez et al., 2017; Tlusty et al., 2018).

This long-term spatial persistence was particularly evident for Bluefin tuna fattening operations, which remained restricted to a limited number of established offshore locations throughout the study period, reflecting the specialized operational requirements of this production system.

Overall, these findings indicate that the evolution of Tunisian marine aquaculture has been characterized by spatial consolidation rather than continuous geographical expansion, reflecting the progressive maturation of the sector and the long-term importance of selecting environmentally and operationally suitable farming locations.

4.2. Infrastructure modernization and offshore expansion

Beyond Following the stabilization of concession allocation (Figure 4), the evolution of Tunisian sea-based marine aquaculture has been characterized primarily by the modernization of production infrastructure rather than continued geographical expansion. The progressive replacement of small cages by standardized 25 m production units (Figure 7), the increasing prevalence of double- and multi-line farm configurations, and the gradual relocation of production towards deeper waters collectively indicate a transition from extensive development to technological intensification.

The widespread adoption of larger cages reflects a broader international trend towards improving production efficiency while optimizing the use of existing farming areas. Increasing cage volume provides greater rearing capacity without proportionally increasing the occupied marine space, while also improving water exchange, feed distribution, and swimming conditions for cultured fish (Samaras et al., 2017; Føre et al., 2018). Larger production units also reduce operational costs per unit of biomass and facilitate economies of scale, making offshore production more economically efficient (Di Trapani et al., 2014; Chu et al., 2020).

The progressive dominance of 25 m cages observed in this study therefore reflects both technological advancement and operational optimization rather than a simple increase in production capacity.

The concurrent development of larger multi-line farm configurations (Figure 8) further illustrates the increasing industrialization of the sector. Organizing cages into more structured layouts improves farm management, facilitates feeding and harvesting operations, optimizes vessel movements, and enhances the efficiency of maintenance activities. Such configurations also maximize the productive use of existing concession areas while minimizing the need for additional marine space, an approach increasingly promoted within Marine Spatial Planning frameworks to reconcile aquaculture development with competing coastal uses (Gentry et al., 2017b; Lester et al., 2018).

The gradual shift of production towards deeper waters represents a complementary adaptation to offshore farming. Deeper environments generally provide stronger currents and greater water exchange, reducing the accumulation of organic waste beneath cages and improving the dispersion of dissolved nutrients (Holmer, 2010; Chu et al., 2020). These conditions contribute to maintaining better environmental quality while supporting higher production levels. At the same time, advances in cage engineering and mooring technologies have enabled the safe deployment of larger farming systems under more energetic offshore conditions, expanding the range of environmentally suitable production sites (Føre et al., 2018; Sievers et al., 2022).

The historical reconstruction also highlights the distinct spatial and structural characteristics of bluefin tuna fattening operations. Unlike marine finfish production, which underwent substantial infrastructure modernization and expansion in cage numbers, tuna farming remained limited to a small number of sites using large-diameter cages (Figure 2, 7 and 9) deployed in relatively deep waters (Figure 9 and Appendix I).

This stability reflects the specific nature of tuna fattening, where production relies on the seasonal transfer of wild-caught fish into existing cages rather than continuous hatchery-based production. Consequently, the spatial distribution and infrastructure of tuna farms are primarily determined by operational and biological requirements rather than production expansion, reinforcing the contrasting development trajectories of the two production systems.

Importantly, these structural changes occurred without a corresponding expansion in concession numbers, demonstrating that recent sector growth has relied predominantly on increasing the productivity and efficiency of existing farming areas.

This evolution reflects a progressive shift from spatial expansion towards production optimization, consistent with the development pathways reported for mature offshore aquaculture industries worldwide (Falconer et al., 2020; FAO, 2024; Gentry et al., 2017a).

Overall, the observed increase in cage size, the reorganization of farm layouts, and the transition towards deeper offshore environments demonstrate that the Tunisian marine aquaculture sector has entered a phase of technological maturation in which production growth is increasingly driven by infrastructure modernization rather than the allocation of new farming areas.

4.3. Historical satellite reconstruction as a decision-support tool for sustainable aquaculture planning

The integration of multi-temporal satellite imagery with administrative concession records demonstrates the value of adopting a temporal perspective for understanding aquaculture development.

While administrative databases indicate where aquaculture is authorized, satellite observations reveal where production has occurred, how farming infrastructure has evolved, and whether concessions have remained active over time (Alleway et al., 2016; Kang et al., 2019). Combining these complementary sources therefore provides a more comprehensive representation of sector dynamics than either dataset could achieve independently.

Unlike conventional inventories, which generally provide static information for a single period, the historical geospatial database developed in this study reconstructs more than two decades of spatial evolution.

This long-term perspective makes it possible to identify persistent production areas, infrastructure modernization, concession inactivity, and changing development patterns, thereby providing valuable evidence on the processes that have shaped the sector through time (Alleway et al., 2016; Cardinale et al., 2011). Understanding these historical trajectories is particularly important because present-day farm distribution represents the cumulative outcome of environmental suitability, technological adaptation, economic investment, and management decisions rather than a single planning event (Falconer et al., 2020; Gentry et al., 2017a).

From a planning perspective, historical evidence complements conventional site-selection approaches that primarily evaluate present environmental suitability. Persistent farming areas identified over long time periods represent locations that have repeatedly demonstrated operational and environmental viability, whereas inactive or abandoned concessions may reveal constraints that are not captured by environmental variables alone (Aguilar-Manjarrez et al., 2017; Tlusty et al., 2018). Incorporating these temporal observations into Marine Spatial Planning (MSP), Integrated Coastal Zone Management (ICZM), and the Ecosystem Approach to Aquaculture (EAA) can therefore improve the identification of Allocated Zones for Aquaculture (AZAs), reduce planning uncertainty, and support more adaptive and evidence-based decision-making (Ehler and Douvere, 2009; Aguilar-Manjarrez et al., 2017; Falconer et al., 2020).

The proposed framework (Figure 1) also illustrates the evolving role of Earth Observation in aquaculture management. While recent studies have focused on automated farm detection using synthetic aperture radar (SAR), high-resolution optical imagery, and artificial intelligence (Fu et al., 2019; Jiang and Ma, 2020; Sui et al., 2020; Xia et al., 2026), this study demonstrates that archived satellite imagery can provide equally valuable information by reconstructing long-term development trajectories. This complementary use of historical Earth Observation extends its application beyond routine monitoring, providing strategic information for evaluating past planning decisions, supporting adaptive management, and guiding sustainable aquaculture development under increasing competition for marine space (Falconer et al., 2020; Gentry et al., 2017b).

Overall, the study workflow demonstrates that understanding how aquaculture has evolved through time is as important as identifying where farming currently occurs. Incorporating this temporal dimension into spatial planning frameworks can improve the long-term sustainability and resilience of marine aquaculture development.

4.4 Limitations and future perspectives

Several limitations should be considered when interpreting the reconstructed historical dataset. Before the launch of the Sentinel-2 mission in 2015, the availability of suitable satellite imagery was irregular, resulting in temporal gaps and variable image quality. Consequently, the reconstructed inventory reflects the aquaculture infrastructure visible in the available imagery rather than a complete annual census. Similar limitations related to image availability, cloud cover, acquisition frequency, and seasonal farm operations have been widely recognized in remote-sensing studies of marine aquaculture (Szuster et al., 2008; Russell et al., 2020; Sui et al., 2020).

The spatial resolution of Sentinel-2 imagery also constrains the characterization of individual cage geometry. Although the adopted methodology successfully identified farm layouts, infrastructure evolution, and standardized cage-size classes, closely spaced cages and small differences in cage diameter cannot always be resolved using medium-resolution imagery alone (Russell et al., 2020). Consequently, the generated database should be interpreted primarily as a robust representation of farm-scale spatial dynamics rather than an engineering inventory of individual cage dimensions.

Despite these limitations, integrating multi-temporal satellite observations with administrative concession records proved sufficiently robust to reconstruct long-term patterns of sector development, including concession dynamics, infrastructure modernization, and offshore expansion.

The complementary use of these independent information sources also reduced the uncertainties associated with relying exclusively on either administrative records or satellite imagery, thereby increasing the reliability of the reconstructed historical database (Alleway et al., 2016; Falconer et al., 2020).

Future research should further enhance this framework through the integration of Sentinel-1 SAR imagery, very-high-resolution optical imagery, artificial intelligence, and object-based image analysis to improve the automated detection and characterization of aquaculture infrastructure under a wider range of environmental conditions (Jiang and Ma, 2020; Sui et al., 2020; Xia et al., 2026). Coupling these advances with targeted field validation, production records, and environmental monitoring would further strengthen long-term assessments and expand the application of historical geospatial datasets for adaptive aquaculture management and marine spatial planning (Aguilar-Manjarrez et al., 2017; Falconer et al., 2020).

Conclusion

This study establishes a unique historical geospatial database documenting more than two decades of sea-based marine aquaculture development in Tunisia. Beyond its contribution to understanding the sector's evolution, this database provides a dynamic baseline that can be continuously updated as new satellite imagery, concession records, and field observations become available, ensuring that it remains an evolving resource rather than a static inventory.

Its long-term value lies in its potential to support evidence-based decision-making. Regular updates will enable the monitoring of infrastructure changes, concession status, farm expansion or relocation, and emerging development trends, while facilitating the evaluation of planning decisions through time. Coupled with environmental, production, and socio-economic information, the database could support concession management, the identification and revision of Allocated Zones for Aquaculture, cumulative impact assessments, environmental monitoring, and the periodic revision of marine spatial planning strategies.

By transforming historical observations into an operational decision-support resource, the proposed framework provides a practical foundation for more adaptive, transparent, and data-driven governance of marine aquaculture in Tunisia and can be readily adapted to other coastal regions facing similar planning challenges.

Acknowledgments

The authors gratefully acknowledge all individuals and institutions who contributed to the collection of the data used in this study. Their support and collaboration were instrumental in the successful completion of this work.

Data Availability Statement

The administrative datasets used in this study were provided by the Tunisian Directorate General of Fisheries and Aquaculture (DGPA) and collaborating national institutions. The geospatial database generated during the study is not publicly available because it contains concession-related information subject to institutional confidentiality and authorization. Access to this data may be considered upon reasonable request and with the permission of the relevant institutions.

References

1. Aguilar-Manjarrez, J., Soto, D. & Brummett, R.E. (2017). *Aquaculture zoning, site selection and area management under the ecosystem approach to aquaculture: a handbook*. Rome, FAO
2. Alleway, H.K., Thurstan, R.H., Lauer, P.R. & Connell, S.D. (2016). Incorporating historical data into aquaculture planning. *ICES Journal of Marine Science*, 73(5), 1427-1436. https://doi.org/10.1093/icesjms/fsv191
3. Cardia, F. & Lovatelli, A. (2015). *Aquaculture operations in floating HDPE cages: a field handbook*. (FAO Fisheries and Aquaculture Technical Paper, 593). Rome, FAO.
4. Cardinale, M., Bartolino, V., Llope, M., Maiorano, L., Sköld, M. & Hagberg, J., (2011). Historical spatial baselines in conservation and management of marine resources. *Fish and Fisheries*, 12(3), 289-298. https://doi.org/10.1111/j.1467-2979.2010.00393.x
5. Cheney, D., Langan, R., Heasman, K., Friedman, B. & Davis, J. (2010). Shellfish Culture in the Open Ocean: Lessons Learned for Offshore Expansion. *Marine Technology Society Journal*, 44(3), 55-67. https://doi.org/10.4031/MTSJ.44.3.6
6. Choung, Y.J., & Jo, M.H. (2020). Comparison of machine learning methods for mapping sea farms with high spatial resolution imagery. *International Journal of Remote Sensing*, *41*(15), 5657-5668. https://doi.org/10.1080/01431161.2019.1701214
7. Chu, Y.I., Wang, C.M., Park, J.C., & Lader, P.F. (2020). Review of cage and containment tank designs for offshore fish farming. *Aquaculture*, 519, 734928. https://doi.org/10.1016/j.aquaculture.2020.734928
8. Corner, R.A., Aguilar-Manjarrez, J., Massa, F. & Fezzardi, D. (2020). Multi-stakeholder perspectives on spatial planning processes for mariculture in the Mediterranean and Black Sea. *Reviews in Aquaculture, 12*(1), 347-364. https://doi.org/10.1111/raq.12321
9. Di Trapani, A.M., Sgroi, F., Testa, R. & Tudisca, S. (2014). Economic comparison between offshore and inshore aquaculture production systems of European sea bass in Italy. *Aquaculture*, *434*, 334-339. https://doi.org/10.1016/j.aquaculture.2014.09.001
10. Ehler, C. & Douvere, F. (2009). *Marine Spatial Planning: A Step-by-Step Approach Toward Ecosystem-Based Management*. (IOC Manual and Guides, 53, ICAM Dossier No. 6). Paris, UNESCO.
11. European Commission (2021). Strategic Guidelines for a More Sustainable and Competitive EU Aquaculture for the Period 2021 to 2030 (COM 2021 236 final). *Official Journal of the European Union*.
12. European Commission (2024). MAPAMED: Marine Protected Areas in the Mediterranean. (Accessed 21

January 2026). https://www.mapamed.org.
13. Falconer, L., Middelboe, A.L., Kaas, H., Ross, L.G. & Telfer, T.C. (2019). Use of geographic information systems for aquaculture and recommendations for development of spatial tools. *Reviews in Aquaculture*, 12(2), 664-677. https://doi.org/10.1111/raq.12345
14. FAO (2024). *The State of World Fisheries and Aquaculture 2024 - Blue Transformation in action*. Rome, FAO. https://doi.org/10.4060/cd0683en
15. FAO (2025). *The State of Mediterranean and Black Sea Fisheries 2025*. General Fisheries Commission for the Mediterranean. Rome. https://doi.org/10.4060/cd7701en
16. Føre, M., Alver, M.O., Alfredsen, J.A., Senneset, G., Espmark, Å. & Terjesen, B.F. (2018). Modelling how the physical scale of experimental tanks affects salmon growth performance. *Aquaculture 495*, 731-737. https://doi.org/10.1016/j.aquaculture.2018.06.057
17. Froehlich, H.E., Gentry, R.R. & Halpern, B.S. (2017). Conservation aquaculture: Shifting the narrative and paradigm of aquaculture's role in resource management. *Biological Conservation 215*, 162-168. https://doi.org/10.1016/j.biocon.2017.09.012
18. Fu, Y., Deng, J., Ye, Z., Gan, M., Wang, K., Wu, J., Yang, W. & Xiao, G. (2019). Coastal Aquaculture Mapping from Very High Spatial Resolution Imagery by Combining Object-Based Neighbor Features. *Sustainability*, 11(3), 637. https://doi.org/10.3390/su11030637
19. Gentry, R.R., Froehlich, H.E., Grimm, D., Kareiva, P., Parke, M., Rust, M., Gaines, S.D. & Halpern, B.S. (2017a). Mapping the global potential for marine aquaculture. *Nature Ecology & Evolution, 1*(9), 1317-1324. https://doi.org/10.1038/s41559-017-0257-9
20. Gentry, R.R., Lester, S.E., Kappel, C.V., White, C., Bell, T.W., Stevens, J. & Gaines, S.D. (2017b). Offshore aquaculture: Spatial planning principles for sustainable development. *Ecology and Evolution, 7*(2), 733-743. https://doi.org/10.1002/ece3.2637
21. Holmer, M. (2010). Environmental issues of fish farming in offshore waters: perspectives, concerns and research needs. *Aquaculture Environment Interactions*, 1(1), 57-70. https://doi.org/10.3354/aei00007
22. Hovik, S. & Stokke, K. B. (2007). Balancing aquaculture with other coastal interests: A study of regional planning as a tool for ICZM in Norway. *Ocean & Coastal Management, 50* (11-12), 887-904. https://doi.org/10.1016/j.ocecoaman.2007.05.003
23. Jiang, Z. & Ma, Y. (2020). Accurate extraction of offshore raft aquaculture areas based on a 3D-CNN model. *International Journal of Remote Sensing, 41*(14), 5457-5481. https://doi.org/10.1080/01431161.2020.1737340
24. Kang, J., Sui, L., Yang, X., Liu, Y., Wang, Z., Wang, J., Yang, F., Liu, B. & Ma, Y. (2019). Sea Surface-Visible Aquaculture Spatial-Temporal Distribution Remote Sensing: A Case Study in Liaoning Province, China from 2000 to 2018. *Sustainability, 11*(24), 7186. https://doi.org/10.3390/su11247186
25. Kapetsky, J.M., Aguilar-Manjarrez, J. & Jenness, J. (2013). *A global assessment of offshore mariculture potential from a spatial perspective*. (FAO fisheries and aquaculture technical paper, 549). Rome, FAO.
26. Lester, S.E., Stevens, J.M., Gentry, R.R., Kappel, C.V., Bell, T.W., Costello, C.J., Gaines, S.D., Kiefer, D.A., Maue, C.C., Rensel, J.E., Simons, R.D.,

Washburn, L. & White, C. (2018). Marine spatial planning makes room for offshore aquaculture in crowded coastal waters. *Nature Communications,* 9, 945. https://doi.org/10.1038/s41467-018-03249-1

27. Ottinger, M., Clauss, K., & Kuenzer, C. (2017). Large-Scale Assessment of Coastal Aquaculture Ponds with Sentinel-1 Time Series Data. *Remote Sensing,* *9*(5), 440. https://doi.org/10.3390/rs9050440
28. Priyanto, I., Hartanto, C.A., & Arymurthy, A.M. (2020). Change Detection of Floating Net Cages Quantities Utilizing Faster R-CNN. In: *3rd International Conference on Computer and Informatics Engineering (IC2IE)*. IEEE, Yogyakarta, Indonesia. 140-145. https://doi.org/10.1109/IC2IE50715.2020.9274685
29. Ross, L.G., Mendoza Q.M., E.A., & Beveridge, M.C.M., (1993). The application of geographical information systems to site selection for coastal aquaculture: an example based on salmonid cage culture. *Aquaculture* 112(2-3), 165-178. https://doi.org/10.1016/0044-8486(93)90442-2
30. Russell, A.G., Castillo, D.U., Elgueta, S.A. & Sierralta, C.J. (2020). Automated Fish Cages Inventorying and Monitoring Using H/A/α Unsupervised Wishart Classification in Sentinel 1 Dual Polarization Data. In: *Latin American GRSS & ISPRS Remote Sensing Conference (LAGIRS).* IEEE, Santiago, Chile, 471-476. https://doi.org/10.1109/LAGIRS48042.2020.9165669
31. Samaras, A., Pavlidis, M., Lika, K., Theodoridi, A. & Papandroulakis, N. (2017). Scale matters: performance of European sea bass, *Dicentrarchus labrax*, L. (1758), reared in cages of different volumes. *Aquaculture Research,* *48*(3), 990-1005. https://doi.org/10.1111/are.12942
32. Sievers, M., Korsøen, Ø., Warren-Myers, F., Oppedal, F., Macaulay, G., Folkedal, O. & Dempster, T. (2022). Submerged cage aquaculture of marine fish: A review of the biological challenges and opportunities. *Reviews In Aquaculture,* *14*(1), 106-119. https://doi.org/10.1111/raq.12587
33. Sui, B., Jiang, T., Zhang, Z., Pan, X. & Liu, C. (2020). A Modeling Method for Automatic Extraction of Offshore Aquaculture Zones Based on Semantic Segmentation. *ISPRS International Journal of Geo-Information,* *9*(3), 145. https://doi.org/10.3390/ijgi9030145
34. Szuster, B.W., Steckler, C., & Kullavanijaya, B. (2008). Detecting and Managing Coastal Fisheries and Aquaculture Gear Using Satellite Radar Imagery. *Coastal Management,* *36*(3),318-329. https://doi.org/10.1080/08920750801968330
35. Tlusty, M.F., Wikgren, B., Lagueux, K., Kite-Powell, H., Jin, D., Hoagland, P., Kenney, R.D. & Kraus, S.D. (2018). Co-Occurrence Mapping of Disparate Data Sets to Assess Potential Aquaculture Sites in the Gulf of Maine. *Reviews in Fisheries Science & Aquaculture* *26*(1), 70-85. https://doi.org/10.1080/23308249.2017.1343798
36. Wang, T., Zhang, X., Xiong, Y., Huang, G. & Chen, J. (2019). Remote Sensing Monitoring and Environmental Pollution Load Assessment of Coastal Aquaculture Area Based on GF-2. In: *8th International Conference on Agro-Geoinformatics (Agro-Geoinformatics), IEEE, Istanbul, Turkey*, 1-6. https://doi.org/10.1109/Agro-Geoinformatics.2019.8820243
37. Wang, Z., Yang, X., Liu, Y. & Lu, C. (2018). Extraction of coastal raft cultivation area with heterogeneous

water background by thresholding object-based visually salient NDVI from high spatial resolution imagery. *Remote Sensing Letters*, 9(9), 839-846. https://doi.org/10.1080/2150704X.2018.1468103

38. Xia, Q., Song, J., Zheng, Q., Zhu, L., Zhang, Y. & Li, B. (2026). Automated mapping for coastal aquaculture ponds based on Google Earth Engine and multi-temporal Sentinel-1/2 data. *Aquaculture* 616, 743709. https://doi.org/10.1016/j.aquaculture.2026.743709
39. Yucel-Gier, G., Arisoy, Y. & Pazi, I. (2010). A Spatial Analysis of Fish Farming in the Context of ICZM in the Bay of Izmir-Turkey. *Coastal Management*, 38(4), 399-411. https://doi.org/10.1080/08920753.2010.498111

Appendix I

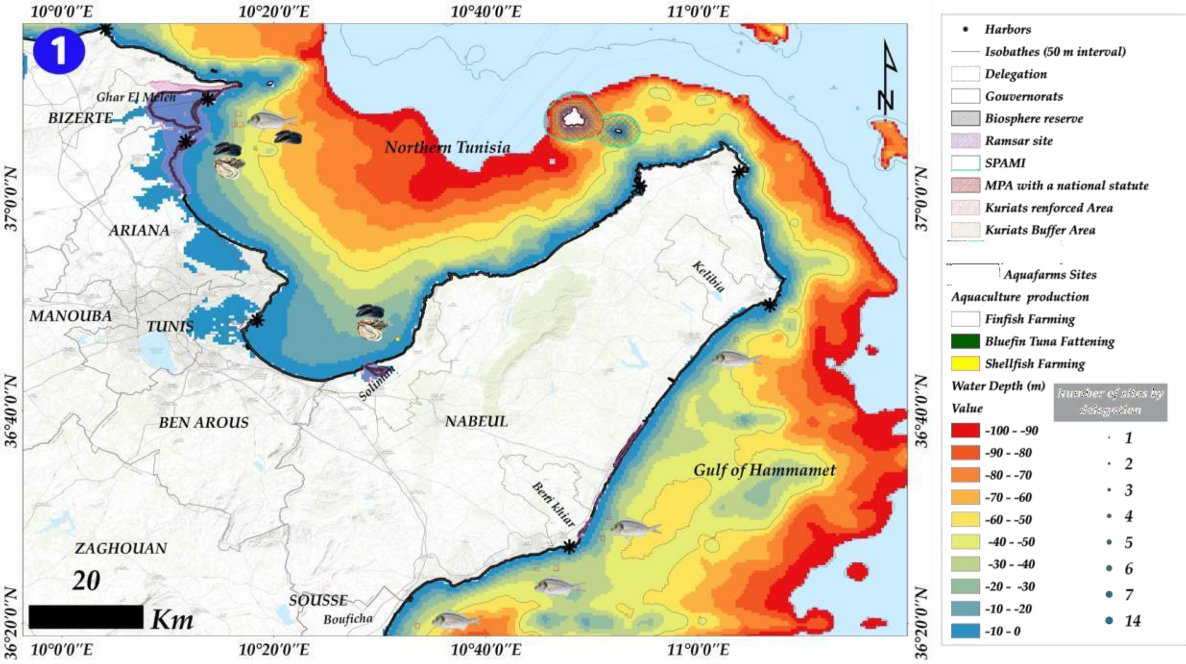


Figure a. Spatial distribution of marine aquaculture concessions (open sea sites) in Tunisia (2004-2026), zoomed area (1) from Figures 3.

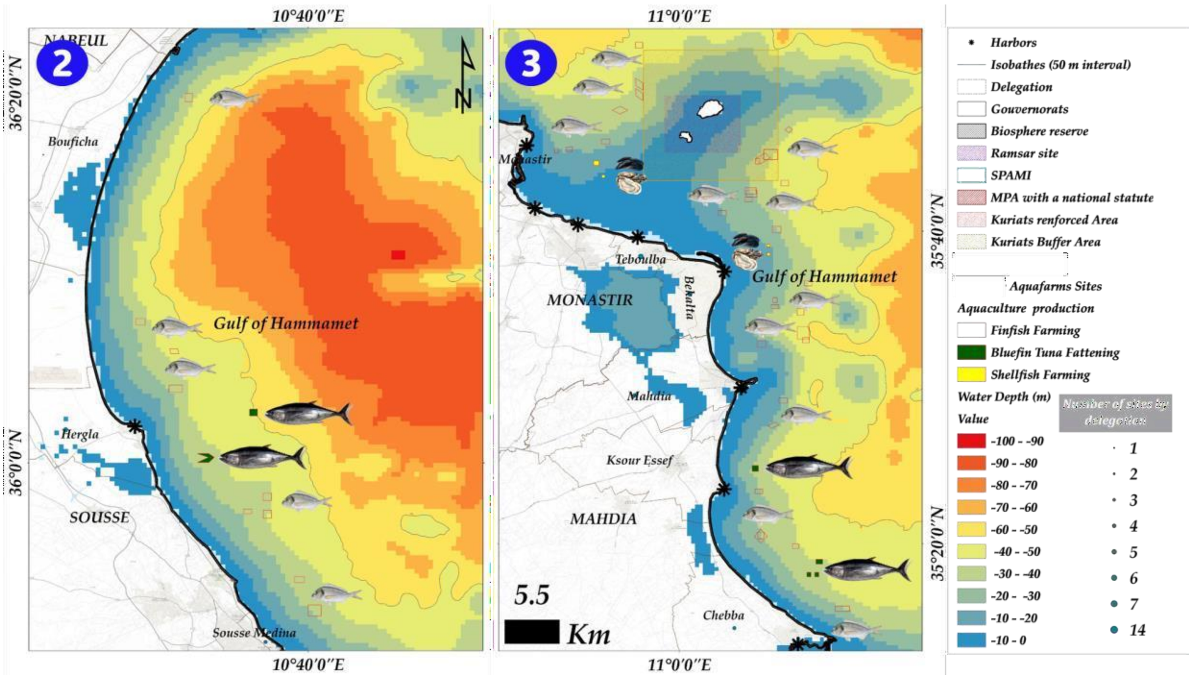


Figure b. Spatial distribution of marine aquaculture concessions (open sea sites) in Tunisia (2004-2026), zoomed areas (2-3) from Figures 3.

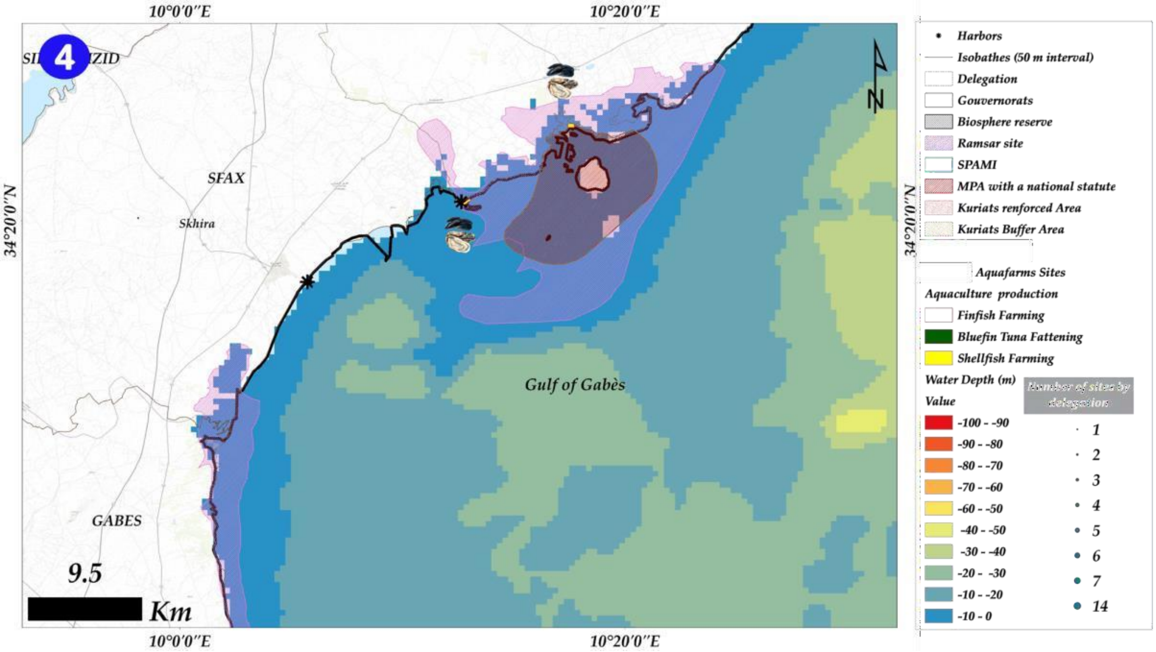


Figure c. Spatial distribution of marine aquaculture concessions (open sea sites) in Tunisia (2004-2026), zoomed area (4) from Figures 3.

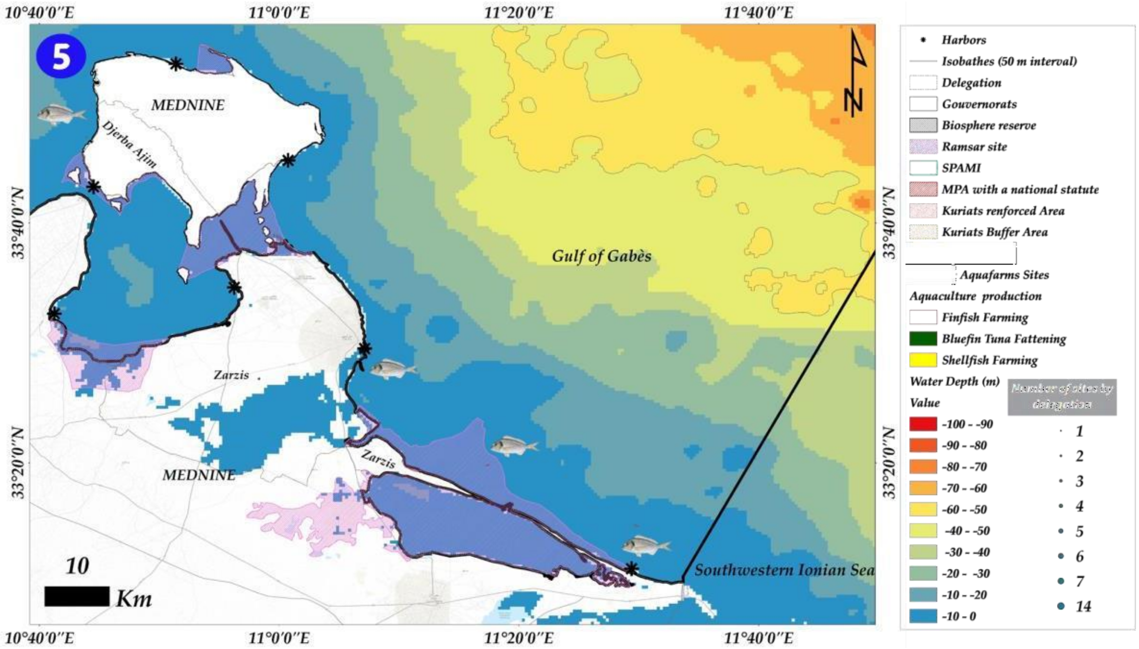


Figure d. Spatial distribution of marine aquaculture concessions (open sea sites) in Tunisia (2004-2026), zoomed area (5) from Figures 3.