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Abstract

The European eel (*Anguilla anguilla*) has experienced a dramatic population decline in recent decades, marked by reduced recruitment, catches, and escapement across its range. Classified as "Critically Endangered" by the IUCN and listed in Appendix II of CITES, the species faces serious conservation concerns. However, information on its biology and health status in North African waters—particularly in Algeria—remains scarce. This study aimed to characterize the demographic structure, growth patterns, feeding ecology, and parasitic infections of *A. anguilla* populations from Lake Tonga (PNEK, El Tarf) and Wadi El-Kebir (Jijel).

Seasonal sampling was conducted at both sites. Following biometric measurements, internal organs (liver, gonads, and digestive tract) were dissected and weighed for growth analyses. Swim bladders and gills were examined to identify parasites and assess tissue damage using the Swim Bladder Degenerative Index (SDI), while otoliths were extracted for age determination.

In both sites, results revealed a predominance of intermediate length and weight classes (400–500 mm; 200–400 g), representing actively growing yellow eels; immature and early maturing stages (I–FII) dominated, indicating primarily function as growth habitats. A strong female bias was observed (3.3:1 in Lake Tonga; 2:1 in Wadi El-Kebir), reflecting environmental influences on sex differentiation.

Morphometric indices, particularly the Ocular Index (OI) and Pectoral Fin Index (PFI), effectively described silvering progression, with a higher proportion of silver eels in Lake Tonga (85%) than in Wadi El-Kebir (60%). Growth analysis indicated negative allometry in Lake Tonga ($b = 2.83$) and near-isometry in Wadi El-Kebir ($b = 2.95$). Seasonal variations in the Gonadosomatic (GSI), Hepatosomatic (HSI), and Empty Gut–Somatic (EGSI) indices reflected synchronized physiological changes linked to silvering and migratory readiness, with peaks in spring and winter.

Feeding analysis revealed marked trophic plasticity: eels from Lake Tonga fed mainly on fish (36%), whereas those from Wadi El-Kebir displayed a more diversified, crustacean-rich diet (29%). Age readings confirmed populations dominated by young and intermediate individuals (1–4 years; mean ≈ 3 years).

Parasitological assessment identified six taxa: *Pseudodactylogyrus* sp., *Ergasilus gibbus*, *Argulus* sp., *Bothriocephalus claviceps*, *Hysterothylacium* sp., and *Anguillicoloides crassus*.

Pseudodactylogyrus sp. exhibited the highest prevalence (>60%), followed by *A. crassus*, whose infection correlated with elevated SDI values, evidencing chronic swim bladder degeneration. These lesions, combined with environmental pressures, underscore the physiological stress imposed by parasitism and its contribution to the continuing decline of *A. anguilla* populations in North Africa.

Résumé

L'anguille européenne (*Anguilla anguilla*) a subi un déclin démographique majeur au cours des dernières décennies, marqué par une forte baisse du recrutement, des captures et du taux d'échappement sur l'ensemble de son aire de répartition. Classée « En danger critique d'extinction » par l'UICN et inscrite à l'Annexe II de la CITES, cette espèce fait face à de graves enjeux de conservation. Cependant, les données concernant sa biologie et son état sanitaire dans les eaux nord-africaines, notamment en Algérie, demeurent limitées. La présente étude vise à caractériser la structure démographique, la dynamique de croissance, l'écologie alimentaire et le parasitisme des populations d'*A. anguilla* des sites du lac Tonga (PNEK, El Tarf) et de l'oued El-Kébir (Jijel).

Des échantillonnages saisonniers ont été réalisés sur les deux sites. Après les mesures biométriques, les organes internes (foie, gonades, tube digestif) ont été prélevés et pesés pour l'analyse de la croissance. Les vessies natatoires et les branchies ont été examinées pour identifier la faune parasitaire et évaluer les lésions à l'aide de l'indice de dégénérescence de la vessie natatoire (SDI), tandis que les otolithes ont servi à la détermination de l'âge des individus échantillonnés.

Au niveau des 2 sites, les résultats montrent la prédominance des classes de taille intermédiaires (400–500 mm ; 200–400 g), correspondant aux anguilles jaunes en phase de croissance active d'une part ; d'autre part, les stades immatures et en début de maturation (I–FII) dominent. Un fort biais en faveur des femelles a été observé (3,3:1 au lac Tonga ; 2:1 à l'oued El-Kébir), confirmant l'influence des conditions environnementales sur la différenciation sexuelle.

Les indices morphométriques, notamment l'indice oculaire (OI) et l'indice de la nageoire pectorale (PFI), se sont révélés efficaces pour évaluer le degré d'argenture, avec une proportion plus élevée d'anguilles argentées au lac Tonga (85 %) qu'à l'oued El-Kébir (60 %). L'analyse de la croissance a révélé une allométrie négative au lac Tonga (b = 2,83) et quasi isométrique à l'oued El-Kébir (b = 2,95). Les variations saisonnières des indices gonado-somatique (GSI), hépato-somatique (HSI) et digestif (EGSI) traduisent des changements physiologiques synchronisés liés à l'argentation et à la préparation à la migration, avec des pics au printemps et en hiver.

L'analyse alimentaire met en évidence une forte plasticité trophique : les anguilles du lac Tonga se nourrissent principalement de poissons (36 %), tandis que celles de l'oued El-Kébir présentent un régime plus diversifié, riche en crustacés (29 %). L'analyse des otolithes

confirme des populations dominées par des individus jeunes et intermédiaires (1–4 ans ; moyenne ≈ 3 ans).

L'étude parasitologique a permis d'identifier six taxons : *Pseudodactylogyrus* sp., *Ergasilus gibbus*, *Argulus* sp., *Bothriocephalus claviceps*, *Hysterothylacium* sp. et *Anguillicoloides crassus*. *Pseudodactylogyrus* sp. présente la prévalence la plus élevée (> 60 %), suivi de *A. crassus*, dont l'infection est associée à des valeurs élevées du SDI, témoignant d'une dégénérescence chronique de la vessie natatoire. Ces lésions, combinées aux pressions environnementales, soulignent la charge physiologique imposée par le parasitisme et son rôle dans le déclin continu des populations d'*A. anguilla* en Afrique du Nord.

ملخص بالعربية

خلال العقود الأخيرة شهدت أسماك الأنقليس الأوروبي تراجعًا حادًا في أعدادها، تميز بانخفاض واضح في معدلات التجنيد والمصايد والهجرة عبر كامل نطاق توزيعها الجغرافي. تُصنَّف هذه الأنواع حاليًا ضمن "الأنواع المهددة بخطر الانقراض الحرج" حسب القائمة الحمراء للاتحاد الدولي لحماية الطبيعة(IUCN) ، كما أُدرجت في الملحق الثاني لاتفاقية الاتجار الدولي بالأنواع المهددة بالانقراض (CITES)وعلى الرغم من أهميتها البيئية والاقتصادية، فإن المعارف المتعلقة ببيولوجيا هذه الأسماك وحالتها الصحية في المياه الإفريقية الشمالية، ولا سيما الجزائرية، ما تزال محدودة. تهدف هذه الدراسة إلى تحليل البنية الديموغرافية، وديناميكية النمو، والنظام الغذائي، والمجتمعات الطفيلية المصاحبة لأسماك الأنقليس في بحيرة تونغا ووادي الكبير.

أُجريت عمليات جمع موسمية للعينات في كلا الموقعين. وبعد القياسات المورفولوجية، استُخرجت الأعضاء الداخلية (الكبد، الغدد التناسلية، الجهاز الهضمي) لتحديد مؤشرات النمو. كما فُحصت المثانة الهوائية والخياشيم لتحديد الأنواع الطفيلية وتقييم درجة التلف النسيجي باستخدام مؤشر تدهور المثانة الهوائية(SDI) ، في حين استُخدمت العظام الأذنية (الأوتوليث) لتقدير العمر.

أظهرت النتائج سيادة الفئات الحجمية المتوسطة (400–500 مم؛ 200–400 غ)، والتي تمثل مراحل النمو النشط لدى الأنقليس الأصفر. كما غلبت المراحل غير الناضجة أو في بداية النضج(I–FII) ، مما يشير إلى أن كلا الموقعين يمثلان مناطق رئيسية للنمو. وسُجّل اختلال واضح في نسبة الجنس لصالح الإناث (3.3:1 في بحيرة تونغا و2:1 في وادي الكبير)، مما يؤكد تأثير العوامل البيئية في تحديد الجنس.

أظهرت المؤشرات المورفومترية، لاسيما مؤشر العين (OI) ومؤشر الزعنفة الصدرية(PFI) ، كفاءتها في تمييز مرحلة النضج الفضي، حيث بلغت نسبة الأسماك الفضية 85٪ في بحيرة تونغا مقابل 60٪ في وادي الكبير. أظهر تحليل النمو علاقة تضعف فيها زيادة الوزن بالنسبة للطول في بحيرة تونغا($b = 2.83$) ، بينما كانت شبه متكافئة في وادي الكبير .($b = 2.95$) كما كشفت المؤشرات الفسيولوجية الموسميةGSI ، HSI، EGSIعن تغيرات متزامنة مرتبطة بمرحلة النضج والاستعداد للهجرة، مع قيم قصوى خلال فصلي الربيع والشتاء.

أظهر التحليل الغذائي مرونة تغذوية عالية، إذ اعتمدت أسماك بحيرة تونغا أساسًا على الأسماك (36٪)، في حين أظهرت أسماك وادي الكبير نظامًا غذائيًا أكثر تنوعًا وغنيًا بالقشريات (29٪). وأكد تحليل الأعمار هيمنة الأفراد الصغيرة والمتوسطة (1–4 سنوات؛ بمتوسط ≈ 3 سنوات).

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Introduction:

For a long time, eels have fascinated humanity due to their economic importance and mysterious nature. They serve both as an essential food resource and a captivating study subject for researchers investigating animal migration and reproductive ecology. Beyond their practical utility, eels intrigue us with their unique morphology, distinguishing them from other fish through their serpentine shape and enigmatic mechanisms. Their ability to move across diverse terrains, along with their tendency to inspire narratives imbued with mystery, further enhances their status as captivating creatures—sometimes even regarded as divine in certain cultures. Some scholars and cultural traditions perceive eels not only as enigmatic organisms but also as metaphysical entities that transcend human intelligence (Tsukamoto & Kuroki, 2014).

Before making the incredible journey of 5,000–10,000 km to the Sargasso Sea to spawn and perish, the European eel (*Anguilla anguilla*), a catadromous species, spends the majority of its life in continental, brackish, or freshwater environments throughout Europe and North Africa. This journey has been verified by both historical surveys of larvae and recent satellite tracking of adult eels arriving at the presumed breeding grounds (Aarestrup et al., 2009; Ginneken & Maes, 2005; Wright et al., 2022).

From an ichthyological perspective, the European eel is one of the species with the widest range of habitats, including brackish waters (bays, fjords, lagoons, estuaries) as well as lotic (rivers, streams, torrents) and lentic (lakes, ponds, canals) freshwater environments (Adam, 1997). This habitat diversity highlights the eel's remarkable adaptability to various ecological conditions, conferring it significant biological and commercial importance.

Ecologically, the eel plays a fundamental role as a "bio-integrator" of environmental quality (Feunteun, 2002). Its bio-integration potential is evident at various spatial and temporal scales (Baisez & Laffaille, 2005). Within an entire watercourse, its presence indicates the existence and accessibility of diverse habitats (marshes, floodplains, river headwaters, etc.). It reflects high physico-chemical water quality, as it is particularly vulnerable to diffuse pollution (Robinet & Feunteun, 2002). Additionally, in hydrosystem functioning, the eel contributes significantly to material fluxes (Laffaille et al., 2000).

For these reasons, the European eel should be regarded as an umbrella species (Simberloff, 1998). Its socio-economic importance is also crucial. Apart from the *leptocephalus* larval stage, which is difficult to access, eels can be exploited by humans at all stages of their biological cycle: glass eel, elver, yellow eel, and silver eel. The high demand for eels in European and Asian international markets has led to rising prices, resulting in overexploitation and widespread poaching of the species. Consequently, this has caused a general decline in natural stocks across its entire distribution range (Bruslé, 1994; Dekker, 2003; Farrugio & Elie, 2011; Sabatié & Fontenelle, 2007; Yahyaoui et al.,2004). Moreover, according to the FAO's FISHSTAT database, global production of the European eel has experienced a significant decline since the 1980s, dropping from a total production exceeding 20,000 tons in Europe and the Mediterranean in 1968 to only 7,663 tons in Europe in 2018, representing 94% of global production. Despite these figures, wild stocks are currently in a critical state, with alarmingly low levels of recruitment and spawning biomass, leading to the species being classified as **critically endangered** by the IUCN since 2008 (Farrugio & Elie, 2011).

It is commonly acknowledged that a complex interaction of several natural and man-made causes has led to the decrease of the European eel (*Anguilla anguilla*). Significant factors include overexploitation and extensive fishing of adult and juvenile eels for aquaculture, as well as changes in the Sargasso Sea's oceans and atmosphere that impact larval survival and drift (Aalto et al., 2016; Aschonitis et al., 2017; Drouineau et al., 2018). Habitat loss and fragmentation, including the construction of migration barriers like dams and weirs, have dramatically reduced available habitats and impeded the eel's migratory routes (Aschonitis et al., 2017; Champkin et al., 2024; Drouineau et al., 2018). Chemical contamination and the bioaccumulation of pollutants such as PCBs, PAHs, OCPs, and heavy metals further degrade habitats and threaten eel health (Brusle, 1991). Reduced survival and reproductive success have also been linked to biological concerns, such as biological contamination by pathogenic organisms, including bacteria (Esteve et al., 2007; Vigier, 1997), parasites (Fazio et al., 2008; Lefebvre et al., 2002, 2004), and virus (Haenen et al., 2010; Van Ginneken et al., 2004; van Ginneken et al., 2005).

In Algeria, eel (*Anguilla anguilla*) fishing began three decades ago in various water bodies within the wetland complex of the El Kala National Park. Research on eel pathology has been conducted in different hydrosystems of the extreme northeastern region of Algeria, where this species is present (Djebbari et al., 2009; Loucif et al., 2009). However, these studies have

primarily focused on cataloging diseases found in lakes, lagoons, and rivers, without considering their temporal evolution.

The assessment of *Anguilla anguilla* populations within El Kala National Park and the surrounding northeastern Algerian wetlands indicates that these populations are subject to substantial health pressures, primarily resulting from parasitic infections. Notably, the nematode *Anguillicoloïdes crassus* has been identified as a major pathogenic agent, exhibiting high prevalence across key aquatic ecosystems such as Lake Oubeira, Lake Tonga, and the Mellah Lagoon. This parasite induces severe pathological alterations to the swim bladder, a critical organ for buoyancy regulation and successful spawning migration. Empirical studies have demonstrated considerable spatial and size-related variability in infection intensity. In particular, eels from Lake Oubeira exhibited prevalence rates as high as 67%, with degenerative changes affecting up to 95% of examined swim bladders, irrespective of age class. These pathological manifestations are likely to compromise migratory efficiency and reproductive success, thereby posing a significant risk to the sustainability of regional eel populations (Tahri et al., 2017; Oudjane, 2021; Tahri et al., 2016; Tahri & Panfili, 2023). With *A. crassus* being most prevalent in brackish environments and *Pseudodactylogyrus* sp. in freshwater, the parasite population is often dominated by a small number of species (Samar et al., 2022). Long-term trends in eel health and population viability are challenging to evaluate because, although these studies have documented the kinds and incidence of diseases, there is a dearth of information on how these health concerns have evolved over time. In general, the management of parasitic diseases, which continue to pose a serious danger to the survival of European eels in this distinctive Mediterranean wetland habitat, is intimately related to the sustainability and well-being of the populations of these animals in El Kala National Park (Samar et al., 2022; Tahri & Panfili, 2023).

During autumn, eels are caught in Lake Tonga, Lake Oubeïra, the estuary of the Mafragh—formed by the confluence of the Bounamoussa and El Kébir rivers—and in the El Mellah lagoon. Fishing operations in these water bodies and estuaries have been ongoing for several decades. Eels are captured using traps and fyke nets in lakes. The El Kala region (northeastern Algeria) has recorded an average annual production of approximately 80 tons, most of which is exported to Italy (MPRH Report, 2004).

Until the early 1990s, eel was the primary fishing resource in the El Mellah lagoon, accounting for between 50% and over 80% of the total catch. However, this proportion has since declined, reaching less than 20% by the early 2000s (Kara & Chaoui, 1998).

Despite existing research on this species—currently fragmented and discontinuous—many critical gaps remain, highlighting the need for further data acquisition. Specifically, studies on stock management and population demographics in northern Algerian hydrosystems are required, covering aspects such as size structure, age distribution, sex ratios, growth rates, silvering stages, and the quality of individuals concerning contamination by pollutants or parasites. Moreover, Wadi El-Kebir (Jijel) has never previously been investigated with respect to the biology, population structure, and parasitology of the European eel (*Anguilla anguilla*). Therefore, the present study provides the first comprehensive assessment of this species in this hydrosystem.

Several objectives are set in this thesis:

- Conduct a review of the existing literature to provide a comprehensive synthesis of current knowledge.
- Assess the body condition and model the growth of the sampled individuals. Establish a length-age key for the captured fish.
- Provide a final assessment and propose recommendations and practical actions for the sustainable management of stocks in the studied area.
- Monitor the degree of silvering in eels.
- Collect epidemiological data on the health status of eels from the selected study sites, particularly concerning Anguillicolosis.

PART 1: General Overview of the European Eel

The European eel (*Anguilla anguilla*) is a catadromous species, spending most of its life in continental and coastal waters but migrating thousands of kilometers to spawn in the Sargasso Sea. Its complex life cycle includes oceanic leptocephalus larvae, coastal glass eels, estuarine and riverine elvers and yellow eels, and finally migratory silver eels returning to the open ocean to reproduce and die (Ginneken & Maes, 2005).

Chapter 1. Decline of the species

1. Historical background:

In his work Historia Animalium, Aristotle was the first to question the reproductive mechanisms of eels, noting that neither eggs nor milt had ever been observed in these fish and famously suggesting that eels originated spontaneously from mud and decaying matter rather than through sexual reproduction This belief originated from the inability of early naturalists to identify eel eggs or larvae, which led Aristotle to hypothesize that eels were neither male nor female and instead emerged spontaneously from mud, particularly in environments rich in decaying organic matter and exposed to solar heat (Dekker, 2002; Grassi, 1896; Schepper, 1882). Since even subsequent naturalists were unable to produce concrete proof of eel spawning or eggs, his findings and hypotheses set off a centuries-long mystery and dispute around eel reproduction 135. The old mystery initially put out by Aristotle was ultimately explained in the 20th century when the real reproductive cycle of eels was discovered, exposing their lengthy travels to the Sargasso Sea to breed (Dekker, 2002; Dufour et al., 2003; Grassi, 1896; Schepper, 1882).

Scientific literature has extensively recorded important historical hypotheses about eel reproduction, including as those of Aristotle, Pliny the Elder, Bernard-Germain de Lacépède, and Lazzaro Spallanzani. Early investigations by Aristotle revealed that eels lacked apparent eggs or reproductive organs, which supported the theory that they formed naturally from mud and decomposing debris . Subsequently, Pliny the Elder proposed that eels reproduced by rubbing against rocks, producing new life from the particles that resulted. Based on the absence of eggs or embryos in specimens that were collected, Spallanzani developed the theory that eels must reproduce at sea, whereas Lacépède postulated that eels were viviparous and mated like snakes in the 19th century.(Schepper, 1882) These enduring enigmas remained until the 20th century, when Johannes Schmidt's discovery of eel larvae (leptocephali) in the Sargasso Sea and further investigation ultimately revealed the eels' actual reproductive cycle (Chang et al., 2020; Ginneken & Maes, 2005). Reviews of eel biology and life history go into great length on these historical narratives and how they were ultimately resolved.(Ginneken & Maes, 2005; Schepper, 1882).

The only researcher who came close to the truth was the Italian physicist Lazzaro Spallanzani in his work *Voyage de Spallanzani dans les Deux-Siciles* (1800). He observed that millions of eels were caught in the marshes, lakes, and rivers of Italy and Sicily, yet no eggs or embryos

were ever found inside them. To explain this phenomenon, he proposed a groundbreaking theory for his time: eels reproduce exclusively in the sea.

A century later, between 1900 and 1920, the Danish scientist Johannes Schmidt published his discovery of the European eel's spawning grounds in the Sargasso Sea(Schmidt, 1923). This conclusion was based on a spatiotemporal analysis of leptocephalus larvae collected in the North Atlantic, showing a decreasing size as the samples approached the Sargasso Sea (Fig. 1).

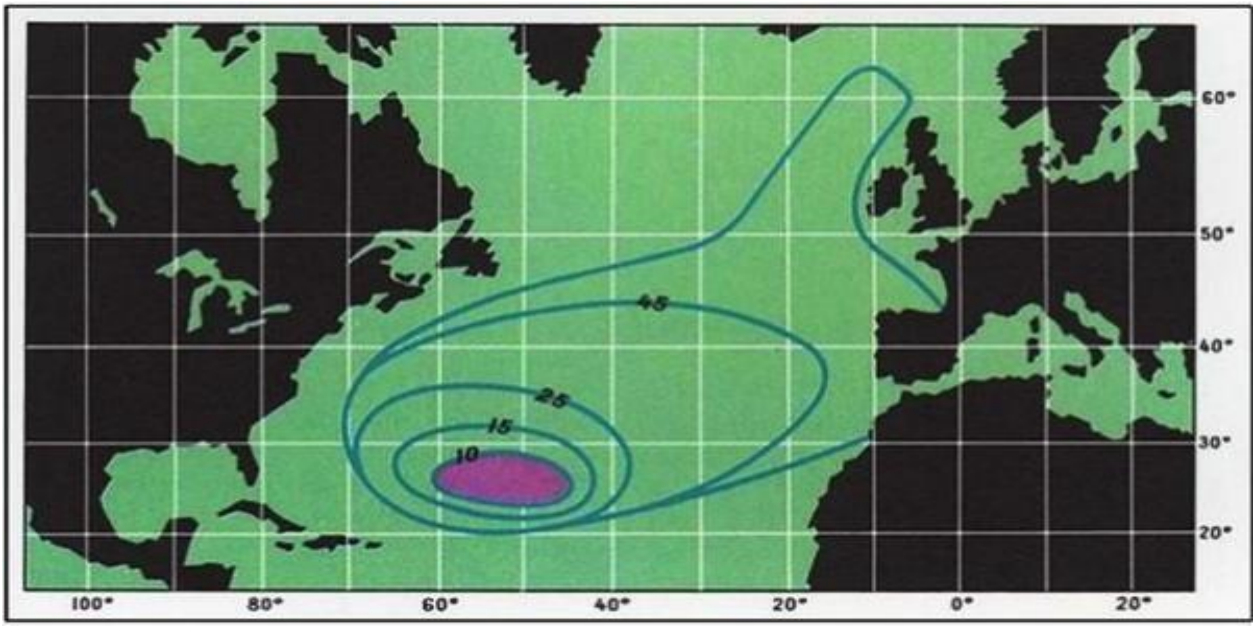

Figure 1: Spawning area and dispersion of leptocephalus larvae of the European eel. The spawning area corresponds to the oceanic surface where larvae smaller than 10 mm are found (Schmidt, 1922).

2. Decline of the European Eel

Until recently, it was believed that all European eels, from Norway to Egypt, belonged to a single stock and thus formed one panmictic population that dispersed randomly during the larval stage (Yahyaoui e t al., 1983; Avise et al., 1990; Tagliavini et al., 1995; Salvadori et al., 1997; Tsukamoto & Aoyama, 1998; Lintas et al., 1998).

The decline of the European eel (*Anguilla anguilla*) is a well-documented phenomenon within the scientific community, with multiple studies identifying its primary causes. Recent research highlights the current state of our knowledge about this remarkable fish, which remains in a precarious, uncertain, and often contentious situation.

The conservation status of the European eel remains critical. It has been listed as Critically Endangered on the IUCN Red List since 2008 and was last assessed in 2018 (Pike et al., 2020). Recruitment indices for glass eels and yellow eels have declined significantly from 1980 to 2011. The quantity of glass eels landed in Europe has decreased over the past 38 years, from 2,000 tons in 1980 to just 60 tons in 2018 (Amilhat et al., 2020). The recruitment index values correspond to the percentage of the geometric mean from 1960 to 1979.

- In the "North Sea" index zone, glass eel recruitment was 0.4% in 2023 (provisional) and 0.7% in 2022 (final).
- In the "Elsewhere in Europe" index series, it was 8.8% in 2023 (provisional) and 11.3% in 2022 (final).
- The recruitment index for yellow eels in 2022 was 9% (final) of the 1960–1979 geometric mean.

Long-term data from 1980 to 2023 indicate that eel recruitment remains at critically low levels.

For several decades, this species has been undergoing an unprecedented crisis, marked by a dramatic population decline. This alarming phenomenon has significant implications for aquatic ecosystems and local economies reliant on eel fisheries.

3. Causes of the Decline of the European Eel

3.1. Climate Change and Oceanic Alterations – Impact on Eel Migrations

Several factors contribute to this alarming decline:

Large-scale changes in marine conditions that impact hatching and larval survival are closely linked to the decline in eel populations in Europe, North America, and East Asia. According to research, changes in ocean temperature, productivity, and currents that affect the availability of food (such as marine snow) and the effectiveness of larval transport from spawning grounds to continental habitats 638 are the most likely causes of the synchronized declines among the three main eel species: European, American, and Japanese eels. For instance, decreasing primary production brought on by climate change has probably reduced the amount of food available to eel larvae, which has resulted in lower survival rates(Bonhommeau et al., 2008; Miller et al., 2014).

Sea surface temperatures have been strongly affected by climate change and by various oceanic characteristics (North Atlantic Oscillation, El Niño-Southern Oscillation, and the North Equatorial Current), which influence the success of eel recruitment in temperate zones. The increase in sea surface temperature caused by climate change has likely led to greater stratification of the Sargasso Sea, resulting in a decrease in primary production. The decline in this primary production could lead to a reduction in food availability for leptocephali, the larval stage of the eel.

A more precise mechanism was recently suggested by(Miller et al., 2016) : the regime shift has led to a decrease in the presence of diatoms and an increase in that of cyanobacteria, which may have resulted in a decline in carbohydrate production, essential for the formation of "marine snow," the primary food source for eel larva(Riemann et al., 2010) .

3.2. Effect on the Migration of Silver Eel Spawners

The migration of European eels (*Anguilla anguilla*) is strongly influenced by climate change and human activities, particularly during the final stages of their life cycle. Several key factors contribute to these effects:

Oceanic conditions and climate change impact river flow, which can, in turn, be indirectly affected by changes in precipitation patterns(Arnell, 1999; Milly et al., 2005). River flow is influenced by variations in precipitation regimes, which are crucial for eel migration(Kettle et al., 2011).Human activities, including water extraction for agriculture, industry, and other uses, further alter river flow patterns(Postel & Richter, 2012; Verreault et al., 2012). Migration occurs more rapidly when river flow is high (Tesch & Thorpe, 2003; Vøllestad et al., 1986) . If the flow is low, migration is delayed, and eels may even be forced to postpone migration until the following year if environmental conditions remain unfavorable(Drouineau et al., 2017; Durif et al., 2000). Finally, a decrease in river flow can lead to an increased proportion of eels passing through turbines. Under low-flow conditions, a greater volume of wate(Bilau et al., 2007; EIFAC, 2009)r is directed through turbines, resulting in higher mortality rates(Bau et al., 2011; Jansen et al., 2007).

3.3. Increased pollution load: contamination of the European eel and consequences on its physiology

Due to their high trophic level and significant lipid storage capacity, eels are particularly vulnerable to contamination by organic pollutants, heavy metals, and pesticides(Belpaire et al., 2011; Belpaire et al., 2009). This sensitivity makes eels useful bioindicators of environmental contamination(Amiard-Triquet et al., 1987; Belpaire & Goemans, 2007; Linde et al., 1996; McHugh et al., 2010). Contamination levels often exceed the thresholds for human consumption (Belpaire et al., 2009; Bilau et al., 2007; EIFAC, 2009), leading to fishing bans in several European regions.

Many sites across Europe (Germany, Belgium, the Netherlands, France, Italy) have imposed fishing restrictions due to contamination (Belpaire et al., 2016). The biological effects of contaminants on fish have been widely documented (Fonseca et al., 2014; Gilliers et al., 2006; Kerambrun et al., 2012), along with the risks for human consumers. While direct eel mortality due to contaminants has been reported in some cases (Dutil et al., 1987; Dutil, 1984), the primary impacts are sublethal. These include tissue damage, stress, disturbances in osmoregulation, behavioral alterations, hormonal disruptions, and genotoxic effects (Belpaire et al., 2009; Couillard et al., 1997).

Being a fatty fish, the eel is particularly vulnerable to pollution. Contaminants accumulate in lipid reserves at high concentrations(Robinet & Feunteun, 2002) and can significantly impact lipid metabolism(Corsi et al., 2005; Fernandez-Vega et al., 1999; Pierron et al., 2007). This is particularly concerning during the silver eel stage, when lipid levels peak (over 13%) to sustain transoceanic migration(Belpaire et al., 2009; van Ginneken & van den Thillart, 2000).

For female eels, 67% of their fat reserves are dedicated to migration and oocyte maturation (Palstra & Van Den Thillart, 2010). Given the lipid mobilization during spawning migration, contaminants are likely to be released into the bloodstream at high concentrations, negatively impacting gonad maturation and oocyte production, as observed in other fish species(Baillon et al., 2015; ICES, 2016; Pierron et al., 2007). These contaminants also affect migration success (Belpaire et al., 2009; Pierron et al., 2008; Robinet & Feunteun, 2002).

3.4. Habitat fragmentation and loss:

According to (Nathan et al., 2008), movement plays a crucial role in foraging, mate-seeking, and predator avoidance. There are different types of movement. The first type, known as *station keeping* (Dingle, 2014) involves localized movements within a home range. According to (Dingle & Drake, 2007), the other two types of movement—*wandering* and *migration*—occur outside the home range.

Movement is often associated with the search for a specific resource (mate, food, etc.) and ends once that resource is obtained (Jeltsch et al., 2013). Migration, however, is usually triggered by physiological and environmental cues rather than the direct search for food or mates. Diadromous fish, such as eels, undergo two major migrations (Tesch & Thorpe 2003). The first migration occurs from spawning grounds to their juvenile growth habitats. During the second migratory movement, eels return to oceanic spawning grounds from their coastal growth areas. Additionally, eels are capable of migrating between various habitats during their continental phase (Arai & Chino, 2012; Béguer-Pon et al., 2015; Daverat et al., 2005; Kaifu et al., 2010; Yokouchi et al., 2012). The extensive construction of dams since the 1950s–1960s has significantly contributed to the decline of eel populations by restricting migration routes and reducing available habitats (Dynesius & Nilsson, 1994; MacGregor et al., 2009; Postel & Richter, 2012). In North America, hydropower dam construction in the St. Lawrence catchment led to a 40% habitat loss for the North American eel (Verreault et al., 2004), while in Europe, habitat loss reached 50%–90% by the late twentieth century (Feunteun, 2002) , In Asia, nearly 75% of Japanese eel habitats were lost between 1970 and 2010, with China experiencing the most severe decline (>80%)(Chen et al., 2014) . Additional anthropogenic pressures, including river channelization, wetland drainage, and land-use changes, have further degraded eel habitats (Elliott & Hemingway, 2008; Postel & Richter, 2012) . The loss of estuarine marshes and intertidal zones due to flood protection infrastructure and agriculture has negatively impacted eel populations(« The Impact of Global Change on the Dynamics of Marine Living Resources », 2014). In Japan, habitat modifications such as river revetment have been linked to declining eel catches and reduced prey diversity (Itakura et al., 2015). Several ecological and genetic factors affect eels' upstream migration during their first year in continental waters. In order to balance trade-offs between growth, survival, and competitiveness, some individuals migrate, while others display resident behavior (Daverat & Tomás, 2006; Drouineau et al.,

2014; Mateo et al., 2017). Social behavior and feeding rates are associated with migration propensity; glass eels that are more sociable and grow more quickly have a higher inclination to migrate (Geffroy & Bardonnet, 2012). Genetic and epigenetic factors also play a role in habitat selection; growth rates and sex ratios are impacted by specific genetic clusters (Côté et al., 2014; Gagnaire et al., 2012).

This process is disrupted by upstream migration obstacles like dams and weirs, which raise eel densities downstream and increase competition, predation risk, and the possibility of sex ratio changes because of density-dependent sex determination (Bevacqua et al., 2011; Poole et al., 1990). Additionally, these obstacles serve as long-term selection pressures, decreasing the fitness of individuals acclimated to freshwater habitats and favoring those suited to downstream ecosystems (Mateo et al., 2017; Podgorniak et al., 2015). Hydropower turbines have a major effect on eel migration downstream, leading to both direct and indirect deaths. death rates from Francis turbines range from 16% to 60%, whereas Kaplan turbines can cause death rates of over 15% and occasionally 100% (Calles et al., 2010; Richkus & Dixon, 2003).

The kind of turbine, site layout, and environmental factors are important determinants of mortality. Fish-friendly trash racks, bypasses, and infrasound barriers are examples of mitigation measures that lower hazards for eel passage, which is dependent on water intake orientation and discharge levels(Bau et al., 2011; Raynal et al., 2013; Sand et al., 2000). Beyond direct mortality, barriers raise the danger of predation, energy expenditure, and migration delays, which may impact reproductive success and put populations under selective pressure(Mateo et al., 2017; Van Den Thillart et al., 2009; van Ginneken & van den Thillart, 2000). To evaluate hydropower impacts, the SEAHOPE model combines death prediction and eel distribution (Jouanin et al., 2012).

3.5. Impact of *Anguillicoloïdes crassus*:

Among alien organisms affecting eels, *Anguillicoloïdes crassus* has the most well-documented and extensive influence on European and American eels. This swim bladder parasite, originally from Japanese eels, was introduced to Europe in the late 1970s to early 1980s, likely through aquaculture (Koops & Hartmann, 1989). It quickly spread throughout Northern Africa (Dhaouadi et al., 2014; Hizem Habbechi et al., 2012) and Europe (Becerra-Jurado et al., 2014; Kennedy & Fitch, 1990; Kirk, 2003) By the mid-1990s, the parasite had also reached North America, with its first recordings in Texas, followed by sightings in Chesapeake Bay and the

Hudson River(Barse & Secor, 1999; Fries et al., 1996). It is now prevalent in both Canada and the United States(Aieta & Oliveira, 2009; Hein et al., 2014). While the transmission of *A. crassus* can occur in brackish waters, its infection rates are generally lower than in freshwater environments(Kirk, 2003). However, due to insufficient comprehensive monitoring, it is challenging to assess the full extent of its occurrence(ICES, 2016).

Figure 2: Massive Infection of the Swim Bladder of Eel by Anguillicoloïdes crassus. (www.flickr.com)

3.6. Fisheries

Eels of all life stages—glass, yellow, and silver—are exploited in both commercial and recreational fisheries employing a variety of fishing methods(Haro et al. 2000; Tesch & Thorpe 2003). The impact of fisheries on eel populations remains uncertain, as all continental life stages are subject to commercial fishing and recreational angling. In Europe, annual eel exploitation is estimated at 25,000–30,000 tons. Fisheries targeting glass eels harvest approximately 800–900 tons per year, representing only 2.7% of the total catch. However, this accounts for more than 2.4 billion juveniles—enough to replenish European waters at a density of 0.1 kg per hectare(Moriarty & Dekker, 1997). In contrast, certain fisheries, particularly in Northern Europe, primarily target silver eels, with an annual yield of about 2,000 tons (Moriarty & Dekker, 1997). While this represents 6.7% of total eel exploitation, substantial portions of silver eel stocks are captured in regions such as Northern Ireland and Norway (Moriarty & Dekker, 1997). In some areas, silver eel escapement is significantly reduced due to intensive fishing pressure (e.g., Cicotti, 1997; Fontenelle et al., 1997). Meanwhile, yellow eels are mainly fished in Mediterranean coastal lagoons and are either sold as juveniles to Italian valliculture systems or exported to Northern Europe for aquaculture and restocking purposes.

The overexploitation of eels has largely resulted from reliance on wild glass eels, especially following domestic shortages in Japan during the 1970s, which intensified fishing efforts in

North America and Europe(Haro et al., 2000; Lee et al., 2003). This rising demand led to a sharp increase in glass eel prices, which tripled between 1993 and 1997, triggering a major economic rush(Ringuet et al., 2002). By the early 2000s, Europe was exporting nearly half of its eel production to Asia, making eels the most economically valuable landed species in France(Briand et al., 2007; Castelnaud, 2001). However, intense commercial and illicit fisheries severely depleted stocks, with alarming exploitation rates recorded in France, Spain, Canada, and Taiwan(Aranburu et al., 2016; Drouineau et al., 2016; Jessop, 2000).

To mitigate overfishing, regulatory measures were introduced. The European Eel Regulation mandated that 60% of captured eels be allocated for restocking, while the species was listed under Appendix II of CITES, leading to trade restrictions and a full EU export ban in 2010(Nijman, 2015). Japan outlawed glass eel fisheries and imposed strict permit requirements for research and aquaculture, with China and Taiwan implementing similar restrictions. Despite these efforts, eel populations remain under serious threat due to persistent illegal fishing and black-market trafficking, posing significant challenges for sustainable management(Drouineau et al., 2016; Nijman, 2015).

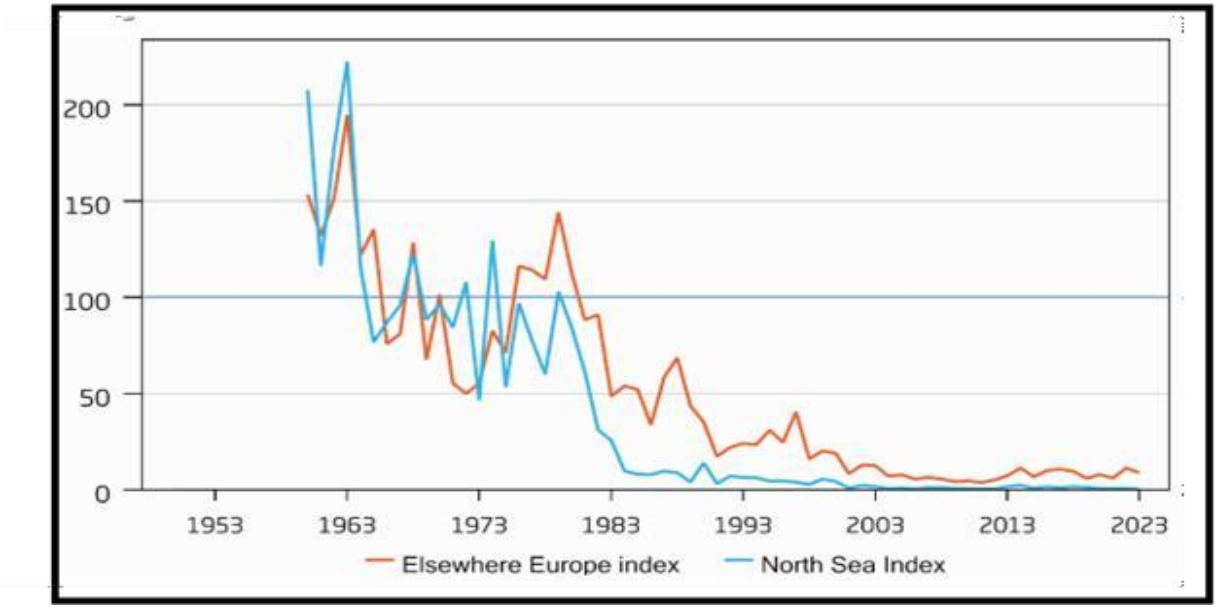

Figure 3: Level of glass eel recruitment (i.e. additions of individuals to the population) from 1960 to 2023, compared with a baseline with value 100 representing the 1960 to 1979 average (ICES, 2024)

3.7. Predation:

Although European eels are naturally at risk from predators, recent studies indicate that this is not the main cause of their sharp population drop. In order to reduce the risk of predation at different times of their lives, eels have developed life-history behaviors and techniques, such as choosing their habitat and migrating efficiently, which helps populations survive in the wild 2. However, additional hazards like human noise might weaken eels' defenses against predators by decreasing their capacity to recognize and flee assaults, particularly when they are young(Righton et al., 2025; Simpson et al., 2015). While predation may contribute to mortality, the overwhelming evidence points to other factors—such as habitat loss, overfishing, pollution, barriers to migration, parasitism, and especially large-scale changes in oceanic conditions—as the main causes of the European eel's decline(Bevacqua et al., 2011; Drouineau et al., 2018; Righton et al., 2025). Consequently, while predation (and heightened susceptibility to it as a result of human influences) contributes, it is viewed as a secondary component about the larger range of anthropogenic and environmental stresses that the species faces (Drouineau et al., 2018; Righton et al., 2025; Simpson et al., 2015).

Yellow eels fall prey to several predators, including cormorants, herons, grebes, and gulls, as well as to mammals such as otters (Tesch, 1985). In addition, some cases of cannibalism have also been reported (Moriarty, 1975).

The quantitative importance of these predations is difficult to assess. Likewise, the negative effects exerted by predators on silver eels during their transatlantic migration and their aggregation in the spawning area are not well understood.

Figure 4: A grey heron nabs a European eel in Aberdeen, Scotland (Kleiner, 2024).

4. Need to be protected

Due mostly to human activity, the European eel is in serious decline. Populations in freshwater, brackish, and marine habitats are severely impacted by intensive fishing. Furthermore, migratory obstacles that interrupt both upstream and downstream migrations, including damming rivers for hydroelectric production, increase the susceptibility of the species. Pollution is a significant hazard as well since it causes physiological stress and habitat deterioration. Parasite infections and changes in the Gulf Stream's path are two other possible variables affecting eel populations. Additionally, illegal, unreported, and unregulated (IUU) fishing and poaching continue to reduce populations, and conservation efforts are continuously

The conservation of the European eel (*Anguilla anguilla*) is governed by the EU Eel Regulation (1100/2007), which aims to restore eel populations through sustainable management strategies. The regulation focuses on increasing the escapement of mature silver eels to their spawning grounds in the Sargasso Sea while ensuring the migration of juvenile glass eels to freshwater habitats. To achieve these objectives, Eel Management Plans (EMPs) have been established at national and regional levels, incorporating measures such as fishing restrictions, habitat restoration, and aquaculture regulations. Effective implementation requires close collaboration among the EU, Member States, and local stakeholders, with financial support available through the European Maritime, Fisheries and Aquaculture Fund (EMFAF).

Over the years, several key actions have been undertaken to reinforce conservation efforts. The EU Eel Regulation was adopted in 2007, requiring the development of long-term eel management strategies at the river basin level. In 2020, an evaluation of the regulation confirmed its relevance but highlighted gaps in implementation. By 2022, the International Council for the Exploration of the Sea (ICES) provided a scientific assessment of Member States' progress in implementing EMPs. In 2023, the EU Marine Action Plan, under the EU Biodiversity Strategy for 2030, emphasized the urgent need for enhanced conservation measures and transboundary cooperation.

At the national level, EU Member States are required to implement strict conservation measures, including facilitating eel migration by ensuring river connectivity, allowing at least 40% of adult eels to return to the sea for spawning, regulating professional and recreational fishing, and restocking suitable inland waters with juvenile eels. Countries that capture juvenile eels (less than 12 cm long) must allocate 60% of their catches for restocking within the EU. To

date, 18 EU countries and a joint Spanish-Portuguese plan for the Minho River have received approval for their management strategies.

The International Union for the Conservation of Nature (IUCN) Red List has listed the European eel (*Anguilla anguilla*) as Critically Endangered since 2008 (Pike et al., 2020; IUCN, 2022). The rule took effect in 2009 after being added to Appendix II of the Convention on International Trade in Endangered Species (CITES) in 2007 (CITES, 2007, 2022). Furthermore, the species was included in the 2014 Convention on the Conservation of Migratory Species of Wild Animals (CMS) Appendix II (CMS, 2018). Further recognizing its critical status, the European eel was added to the OSPAR List of Threatened and/or Declining Species and Habitats in 2008. Despite conservation efforts, its status remains severely compromised across all OSPAR regions (OSPAR, 2022). Moreover, in 2013, the species was also classified as Critically Endangered by the Helsinki Commission (HELCOM) in the Baltic Region (HELCOM, 2013).

Given the severely low stock levels and continued recruitment collapse of the European eel, the International Council for the Exploration of the Sea (ICES) has repeatedly recommended that all human-induced mortality of the species, including fishing, be brought as near to zero as feasible (Aalto et al., 2016; Dekker, 2016). The urgent need to stop future decreases and increase the number of adult eels (silver eels) fleeing to the sea to spawn is reflected in this "zero catch" suggestion, since current escapement is much below the EU's 40% objective and, in some places, is projected to be just about 1% of historical recruitment(Aalto et al., 2016; Diekmann et al., 2018). Based on the panmictic population pattern of the eel, the zero catch recommendation states that overexploitation or insufficient protection in any area can jeopardize recovery for the entire species 25. Given the eel's complicated life cycle and the numerous stresses it experiences, ICES believes that the only realistic opportunity for stock recovery is a total halt to fishing and other anthropogenic deaths(Aalto et al., 2016; Dekker, 2016).

5. European eel in Algeria:

Within these suitable sites (Table 2), the European eel (*Anguilla anguilla*) has a highly restricted distribution in Algeria, being found only in four main locations: Lake Oubeira, Lake Tonga, Mellah Lagoon, and the Mafragh Estuary. These areas represent the only sites in the

country where the species is both naturally present and legally exploited, underscoring its limited distribution in Algeria.

Long-term monitoring has shown that eels inhabiting these environments exhibit rapid growth and earlier maturation compared to their European counterparts, likely due to specific local environmental conditions. Additionally, the sex ratio is strongly skewed toward females, and the transition from the yellow (resident) to silver (migratory) stage occurs earlier, typically between three and four years of age(Tahri & Panfili, 2023).

Table 1: Suitable sites for the exploitation of the European eel in Algeria.

Région	Wilaya	Sites	Latitude	Longiude
Ouest	AinTémouchent	*Oued Tafna*	N 34°41'36	W1°28'17"
	Oran	*La Macta*	N 35.77088	W 0.11682
	Mostagnem	*Oued Chelif*	N 36° 02′ 22	W 0° 07′ 55″
Centre	Chlef	*Oued Tarzout*	N 36°27'53	E 1°0'46" E
	Boumerdes	*Oued Isser*	N 36° 54′ 46	E 3° 51′ 25″
	Béjaia	*Oued Agrioune Tamalahat*	N 36° 32′ 47	E 5° 13′ 47″
Est	Jijel	*Oued El Kébir*	N 36° 32′ 16	E 6° 15′ 54″
	Skikda	*Oued Guebli*	N36° 52 35	E 6° 54′
		Oued El Kébir	N 36.88038	E 6.59188
	El Tarf	*Oued Mafragh*	N 36 50 85	E 7 56 61
		Messida Tonga	N 36 54 49	E 8 31 06
		Lac Oubeira	N 36 51 98	E 8 22 94
		Lac Mellah	N 36° 53 05	E 8 20 61

Chapter .2: Species biology: Taxa, life cycle, reproduction, and migration

1. Systematic Position:

Eels belong to the class Osteichthyes, subclass Apodes, order Anguilliformes, and family Anguillidae, within which they constitute the genus *Anguilla* (Blache, Bauchot & Saldnha, 1973). Their larval stage—leptocephalus—is characterized by a distinct morphology and specific adaptations, and is a defining feature of the superorder Elopomorpha (Historically, two Atlantic species and between 16 and 17 Indo-Pacific species were recognized, depending on the author(F. W. Tesch, 1977). However, (Watanabe et al., 2005), using both morphological and genetic criteria, concluded that there are in fact 15 species worldwide. There is ongoing debate regarding their phylogenetic separationa , and not all spawning grounds have been conclusively identified (Aoyama et al. 2001; Lin et al. 2001; Teng et al. 2009)(Aoyama et al. 1996; 2001; Inoue et al. 2010; Lee et al. 2003). Species distribution area Species distribution area Species distribution area Species distribution area Species distribution area Species distribution area Species distribution area Species distribution area Species distribution area Species distribution area Species distribution area Species distribution area Species distribution area (Miller, 2003). The two Atlantic species are distributed in the Northern Hemisphere, and their identification is primarily based on the number of vertebrae and myomeres (Tesch, 1977; Lecomte-Finiger, 1985). Furthermore, they exhibit distinct geographic distributions:

- The American eel *Anguilla rostrata* (Lesueur, 1817) inhabits the northeastern region of the American continent, ranging from southern Greenland to Venezuela, with a few individuals occasionally found in northern Europe.
- The European eel *Anguilla anguilla* (Linnaeus, 1758) is primarily found in western Europe.

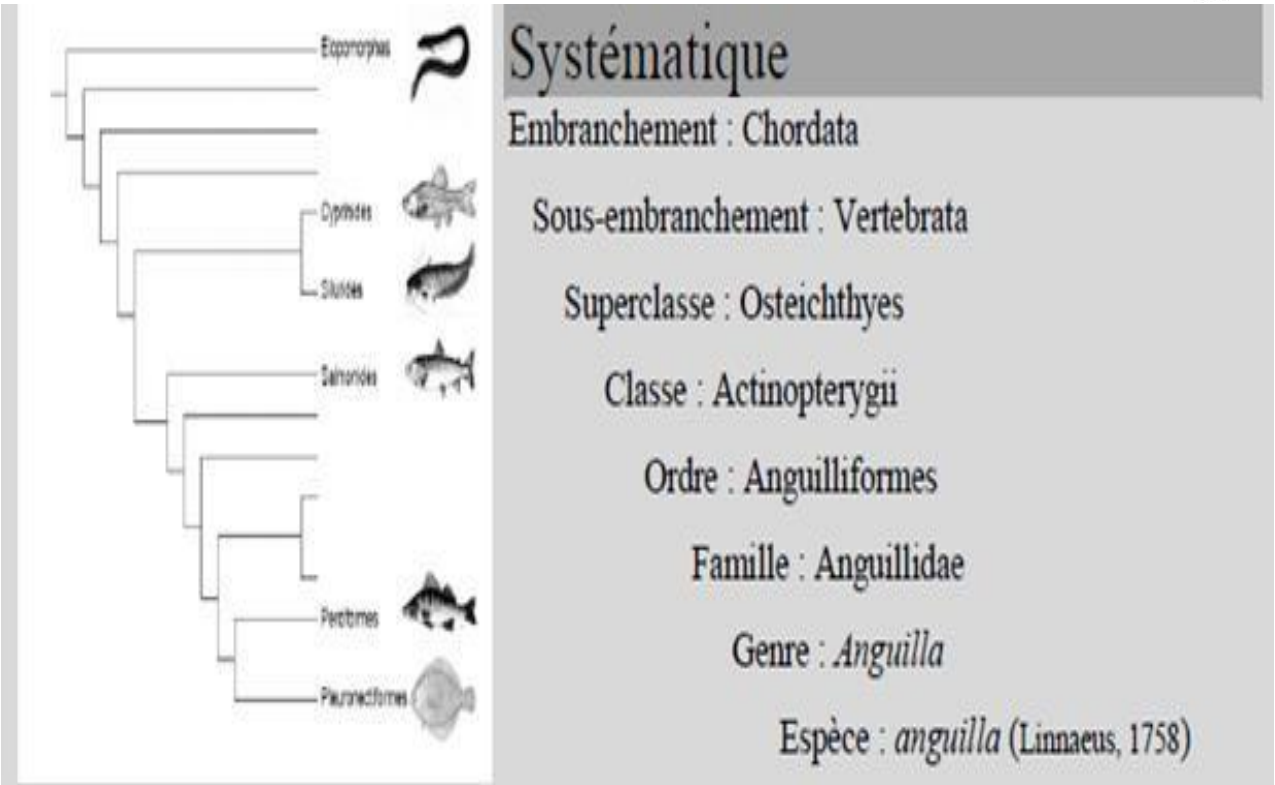

Figure 5: Simplified phylogeny of Teleosts, showing the relative position of Elopomorphs about other major groups, adapted from Rousseau (2000).

Table 2: Geographic distribution of species belonging to the genus Anguilla (Baudrier et al., 2022)

Species	Geographic distribution
Anguilla anguilla (Linnaeus, 1758)	Eastern Atlantic: from Scandinavia to Morocco, Baltic Sea, Black Sea, and Mediterranean Sea
Anguilla australis (Richardson, 1841)	Southwestern Pacific: Australia, New Zealand, New Caledonia
Anguilla bengalensis (Gray, 1831)	Indian subcontinent: Pakistan, India, Sri Lanka, Myanmar
Anguilla bicolor (McClelland, 1844)	Indo-Pacific: Australia, Madagascar, Mozambique
Anguilla breviceps (Chu & Jin, 1984)	China
Anguilla celebesensis (Kaup, 1856)	Western Pacific: from Indonesia to the Philippines and New Guinea
Anguilla dieffenbachii (Gray, 1842)	New Zealand (endemic)

Species	Geographic distribution
Anguilla interioris (Whitley, 1938)	New Guinea
Anguilla japonica (Temminck & Schlegel, 1846)	Japan, China, Taiwan, Korea, Philippines
Anguilla labiata (Peters, 1852)	Eastern Africa: from Kenya to South Africa, Mauritius, Réunion Island
Anguilla luzonensis (Watanabe, Aoyama & Tsukamoto, 2009)	Philippines
Anguilla malgumora (Kaup, 1856)	Borneo, Indonesia, Philippines
Anguilla marmorata (Quoy & Gaimard, 1824)	Indo-Pacific: Mozambique, French Polynesia, Japan
Anguilla megastoma (Kaup, 1856)	Polynesia: from Indonesia to the Society Islands
Anguilla mossambica (Peters, 1852)	Eastern Africa: from Kenya to South Africa, Madagascar, New Caledonia
Anguilla nebulosa (McClelland, 1844)	Eastern Africa, Andaman Islands, Bangladesh, Sri Lanka, Sumatra, Indonesia
Anguilla obscura (Günther, 1872)	New Guinea, Australia, Society Islands
Anguilla reinhardtii (Steindachner, 1867)	New Guinea, Australia, Tasmania, Lord Howe Island, New Caledonia
Anguilla rostrata (Lesueur, 1817)	Greenland, Canada, USA, Panama, southern Lesser Antilles

2. Eel presentation:

The European eel (*Anguilla anguilla*) is a single species within the family Anguillidae, first described by Linnaeus in 1758, and is native to the waters of Western Europe, the Mediterranean, and North Africa(Dekker, 2003; Ginneken & Maes, 2005). In terms of taxonomy, it is closely related to the American eel (*Anguilla rostrata*), both of which spawn in the Sargasso Sea. However, physical characteristics like vertebrae count and genetic markers set them apart. Recent genetic investigations have shown minor but substantial genetic

structure, indicating some degree of isolation by geographical or temporal separation across groups, contrary to the conventional knowledge that European eels constitute a single, randomly mating (panmictic) population(Ginneken & Maes, 2005; Maes & Volckaert, 2002; Wirth & Bernatchez, 2001).

The European eel is a member of the evolutionary archaic teleost fish superorder Elopomorpha. The Elopiformes, which include tarpons, are the most primitive lineage in this group, deriving from the common ancestor of all Elopomorphs. The Albuliformes (bonefishes) and a sister group that includes the Anguilliformes (true eels) and Saccopharyngiformes (deep-sea gulper eels) emerged as a result of further evolution. These two groups share physical characteristics, such as a filamentous caudal fin. The Elopomorpha's monophyly is supported by phylogenetic studies(Inoue et al., 2010)

The characteristic of elopomorphs, such as eels, that sets them apart is their leptocephalus larva, which is iso-osmotic with saltwater and is thought to be evolutionarily primordial among actinopterygians. According to (Hulet, 1989), this larval form probably helped early fishes avoid relying on freshwater for development. This idea is supported by the fact that gill chloride cells in leptocephali emerge later(Sasai et al., 2007).

A snake-like fish with pectoral fins running the length of its body, the European eel (*Anguilla anguilla*) is cylindrical in the lower portion and laterally flattened close to the tail. It is a huge migratory fish that travels between fresh and salt water (amphihaline) and spawns in the sea (thalassotoque), making it unique in Europe among the five eel species present in temperate and subtropical climates 34. The species is semelparous, meaning it reproduces just once before dying, and panmictic, meaning all individuals are members of a single, randomly selected mating population (Harwood et al., 2022; Rohtla et al., 2022).

The genus *Anguilla*, which includes the European eel (*Anguilla anguilla*), is a monophyletic group of freshwater eels that originated from midwater, deep-ocean progenitors in the order Anguilliformes *Anguilla anguilla* and its closest relative, the American eel (*A. rostrata*), comprise a unique Atlantic clade, according to molecular phylogenetic studies utilizing mitochondrial DNA. This clade split from Indo-Pacific ancestors that evolved close to modern-day Indonesia(Aoyama et al., 1996, 2001; Inoue et al., 2010). The westward dispersal of ancestral eels likely occurred via ancient equatorial ocean currents through the Tethys Sea, with the Atlantic lineage entering the paleo-Atlantic and giving rise to both European and American eels(Aoyama et al., 2001). These two species' slight sequence divergence and high

genetic similarity reflect their recent shared origins(Aoyama et al., 1996). About 20 million years ago, the genus Anguilla had a significant radiation that was characterized by many speciation events and geographic expansions. This complicated evolutionary history is reflected in the distinctive migratory behavior of Atlantic eels, especially their spawning in the Sargasso Sea. Because of convergent evolution, physical characteristics like skin color and fin length—which were used in early classifications—are now regarded as untrustworthy. Molecular data, on the other hand, have offered a more reliable foundation for phylogenetic relationship resolution(Aoyama et al., 2001; Y.-S. Lin et al., 2001; Teng et al., 2009). The evolutionary transition from tropical ancestors with short migrations to temperate species like *A. anguilla* with long-distance migrations is a key feature of the group's history Overall, the European eel's phylogeny highlights a deep-ocean origin, westward dispersal, and rapid radiation, resulting in the complex life cycle and broad distribution seen today, all the European eel's phylogeny highlights a deep-ocean origin, westward dispersal, and rapid radiation, resulting in the complex life cycle and broad distribution seen today (Aoyama et al., 1996, 2001; Inoue et al., 2010; Lee et al., 2003).

Figure 6: European Eel (Curnick, 2010).

3. European eel life cycle:

The life cycle of the European eel (*Anguilla anguilla*) is extremely complicated, spanning hundreds of kilometers and several different environments. Adult "silver eels" start their voyage by traveling up to 6,000 kilometers from rivers in Europe and North Africa to the Sargasso Sea, where they breed from December to May before dying.

The eggs hatch into transparent, leaf-shaped larvae called leptocephali, which drift for about a year on ocean currents (such as the Gulf Stream and North Atlantic Current) back toward Europe and North Africa(Ginneken & Maes, 2005; Hsu et al., 2024). Upon reaching coastal waters, the larvae metamorphose into glass eels—small, transparent juveniles—which then migrate into estuaries and freshwater systems, or sometimes remain in brackish habitats(Ginneken & Maes, 2005; Hsu et al., 2024; Teichert et al., 2023).

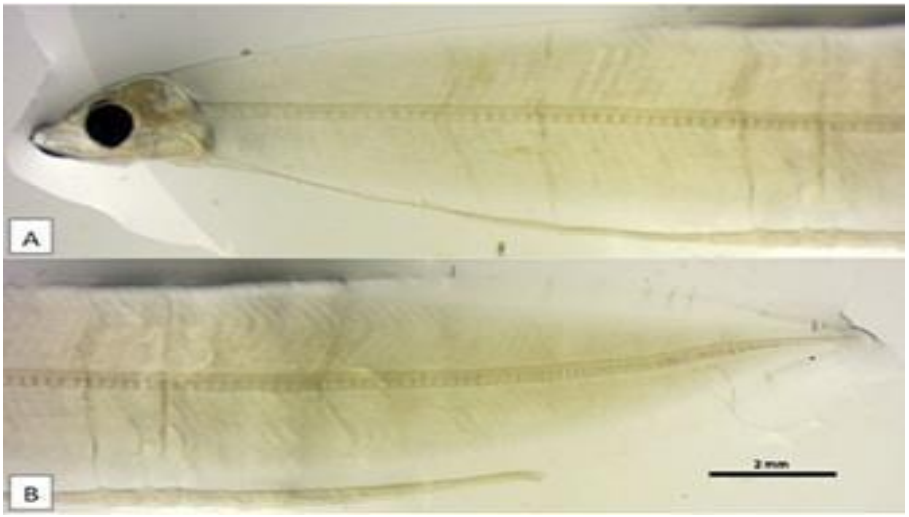

Figure 7: External morphology of leptocephalus larvae of the European eel (*Anguilla anguilla*) (Rønquist Knutsen, 2015).

Glass eels settle and develop into colored "yellow eels," a period that can extend from three to more than thirty years. During this time, their exceptional phenotypic plasticity allows them to grow and adapt to a variety of environmental situations(Enbody et al., 2021; Righton et al., 2025; Teichert et al., 2023)

Figure 8: *Anguilla anguilla* Glass eel. 70 mm TL (Silfvergrip, 2009)

Growth rates, age at maturation, and habitat use during this stage vary widely depending on local conditions, with eels in brackish water often growing faster and reaching larger sizes than those in freshwater (Leo & Gatto, 1995; Teichert et al., 2023).

To prepare for their long-distance migration to the Sargasso Sea, **yellow eels** go through a second metamorphosis called "**silvering,**" which entails major physiological and morphological changes, when they are ready to reproduce. Enlargement of the eyes, changes in body color (such as a darker back and silvery belly), increased fat stores to power the voyage, and structural adjustments to improve swimming efficiency and reproductive potential are all part of this process(Ginneken & Maes, 2005; Pujolar et al., 2015; Righton et al., 2025).

Figure 9: Yellow eel stage and silver eel stage of the European eel (*Anguilla anguilla*). https://forthriverstrust.org/monitoring-eels-in-northern-ireland/

Since the eels do not feed during this period and must rely only on stored energy, these modifications are essential to their survival throughout their continuous migration and successful spawning 79. Gonadal maturation and other internal changes that facilitate reproduction upon arriving at the spawning grounds also occur throughout the silvering phase(Baillon et al., 2015). These physiological and morphological modifications are well-documented and are essential for the completion of the European eel's unique and challenging life cycle(Ginneken & Maes, 2005; Pujolar et al., 2015; Righton et al., 2025).

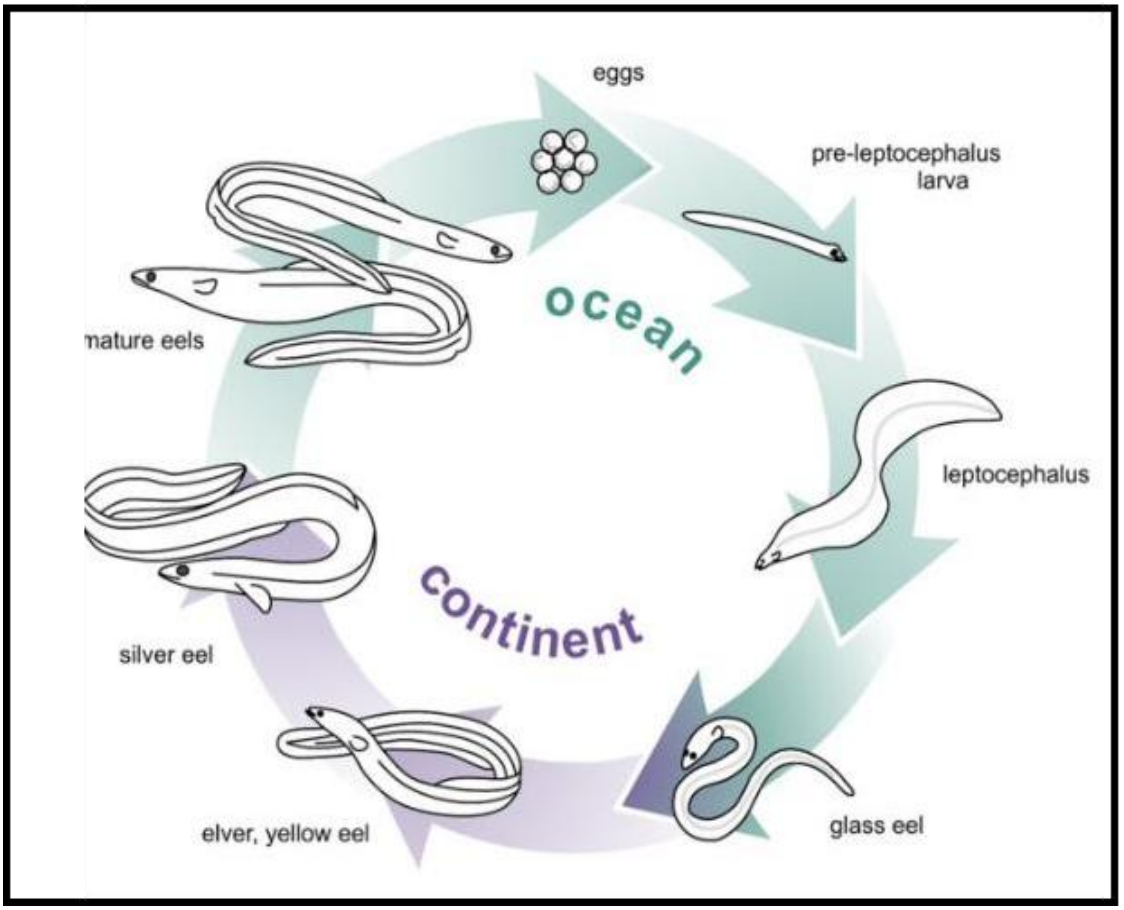

Figure 10: The life cycle of the European eel (Burgerhout et al., 2019).

4. European eel spawning migration:

One of the longest and most enigmatic spawning migrations in the animal kingdom, the European eel travels 5,000–7,000 kilometers from European and North African seas to the Sargasso Sea in the western Atlantic (Aarestrup et al., 2009; Righton et al., 2016; Wright et al., 2022). During their journey, eels exhibit diel vertical migrations—swimming at depths of 100–300 meters at night and descending to 600–1,000 meters during the day—likely as a strategy to avoid predators and manage energy use(Aarestrup et al., 2009; Pelster, 2014; Righton et al., 2016) Migration speeds are highly variable, ranging from 3 to 47 km per day, and not all eels arrive in time for the same spawning season, suggesting a mixed migratory strategy rather than a single synchronized cohort(Righton et al., 2016; Wright et al., 2022) Any damage, such as that caused by a parasite infection, might jeopardize the effectiveness of migration since the swimbladder is essential for buoyancy control during these depth changes. 9. During migration, eels do not consume food; instead, they use their stored energy to power their travels, sexual

development, and spawning(Pelster, 2014). A wide 2,000 km area of the Sargasso Sea is where spawning takes place, and despite sharp population losses, the spawning area has been constant(Miller et al., 2019). Since eels frequently migrate at night to escape predators, the early marine phase—particularly the transition via coastal zones—is a time of greater risk and slower progress.(Lennox et al., 2018) Understanding these migration patterns is vital for conservation, as successful migration is essential for the species' reproduction and recovery(Righton et al., 2016; Stein et al., 2016; Wright et al., 2022)

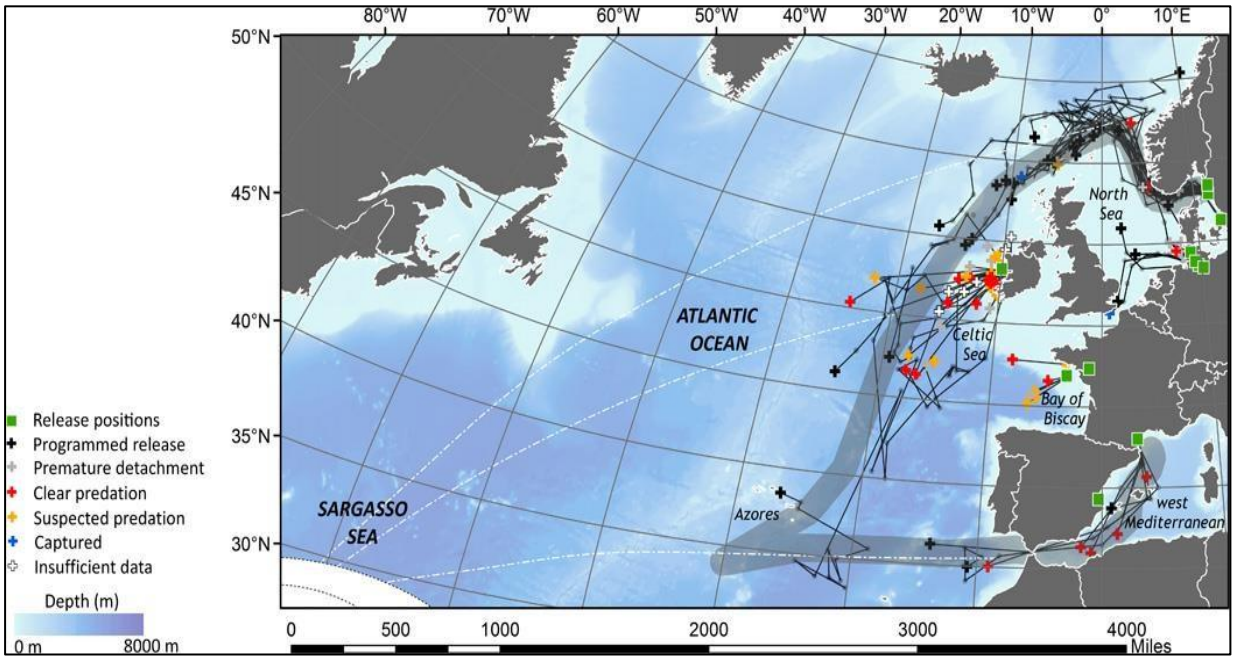

Figure 11: Spawning area (Righton et al. 2016).

5. European Eel reproduction:

A complicated life cycle and distinct reproductive biology define eel reproduction, particularly in the European eel (*Anguilla anguilla*). Due to their semelparous nature, eels migrate thousands of kilometers to the Sargasso Sea to breed once in their last years 97. Usually larger than males, females may lay millions of eggs, and it is thought that spawning occurs in deep ocean waters. Adults then perish(Geffroy & Bardonnet, 2016; A. Palstra et al., 2020). Environmental sex determination is the process by which eels determine their sex based on environmental factors including population density and development rate. Higher densities tend to produce more males(Crowley et al., 2022; Geffroy & Bardonnet, 2016). Gonadal development and sexual differentiation are regulated by specific genes and hormones, with recent research identifying key molecular pathways and gene expression patterns involved in

these processes(Horiuchi et al., 2022; Li et al., 2025) Studies show that dominant males often fertilize most eggs, even when sperm from multiple males is mixed, indicating a hierarchy in reproductive success (Guarniero et al., 2020, 2023) Understanding the mechanisms of sex differentiation, reproductive behavior, and environmental influences is crucial for conservation and aquaculture, given the species' critically endangered status and dramatic population declines (Crowley et al., 2022; Geffroy & Bardonnet, 2016)

6. Distribution Range

The European eel (*Anguilla anguilla*) exhibits an extensive distribution across the eastern North Atlantic, encompassing the coasts of Europe and North Africa, as well as the Mediterranean and Baltic Seas (Dekker, 2003). The species has a unique catadromous life cycle, spawning in the ocean but growing in continental waters. The Danish oceanographer Schmidt (1923) was the first to identify the common spawning area of the two North Atlantic eel species—*A. rostrata* (American eel) and *A. anguilla* (European eel)—in the Sargasso Sea. Seventy years later, Tsukamoto (1990) located the spawning grounds of the Japanese eel (*A. japonica*) near the seamounts east of the Mariana Islands in the North Pacific. A decade after that, Miller et al. (2009) provided strong evidence for the spawning area of the North Pacific population of *A. marmorata* (marbled eel), situated near that of *A. japonica*. For other *Anguilla* species, spawning areas have not yet been definitively located, though hypotheses have been proposed based on Jespersen's (1942) global collections of leptocephalus larvae. However, the inability to assign many larvae to specific species has limited the accuracy of these interpretations.

After spawning, eel larvae are transported across the Atlantic by major ocean currents, including the Gulf Stream and the North Atlantic Drift, eventually reaching the coasts of Europe and North Africa (Munk et al., 2023). Juvenile stages, such as glass eels and elvers, colonize a wide range of habitats—including freshwater rivers and lakes, brackish estuaries, and coastal marine environments—often migrating considerable distances inland through river systems (Domingos et al., 2006; Harwood et al., 2022; Laffaille et al., 2003). Within these systems, eel distribution is influenced by several factors, including habitat type, river barriers, and proximity to the sea. Larger individuals tend to be found in deeper or upstream habitats, whereas smaller eels are more common in downstream areas (Domingos et al., 2006; Harwood et al., 2022; Laffaille et al., 2003).

Historically, *A. anguilla* was widely distributed throughout areas such as the Iberian Peninsula; however, its range has contracted by over 80% in some regions, largely due to river fragmentation and habitat degradation (Clavero & Hermoso, 2015). Despite this fragmentation, the species is considered panmictic, meaning all individuals belong to a single, randomly mating population, which has significant implications for conservation strategies at both local and international scales (Bornarel et al., 2018). This extraordinary life cycle, linking geographically distant freshwater and coastal habitats to a single oceanic spawning area, makes the European eel highly vulnerable to environmental changes in both marine and freshwater ecosystems (Clavero & Hermoso, 2015; Dekker, 2003; Miller et al., 2019).

Within the Anguillidae family, the European eel *Anguilla anguilla* (Linnaeus, 1758) is certainly the species with the widest distribution range. In continental areas (Figure), its range extends across most coastal countries of Europe and North Africa.

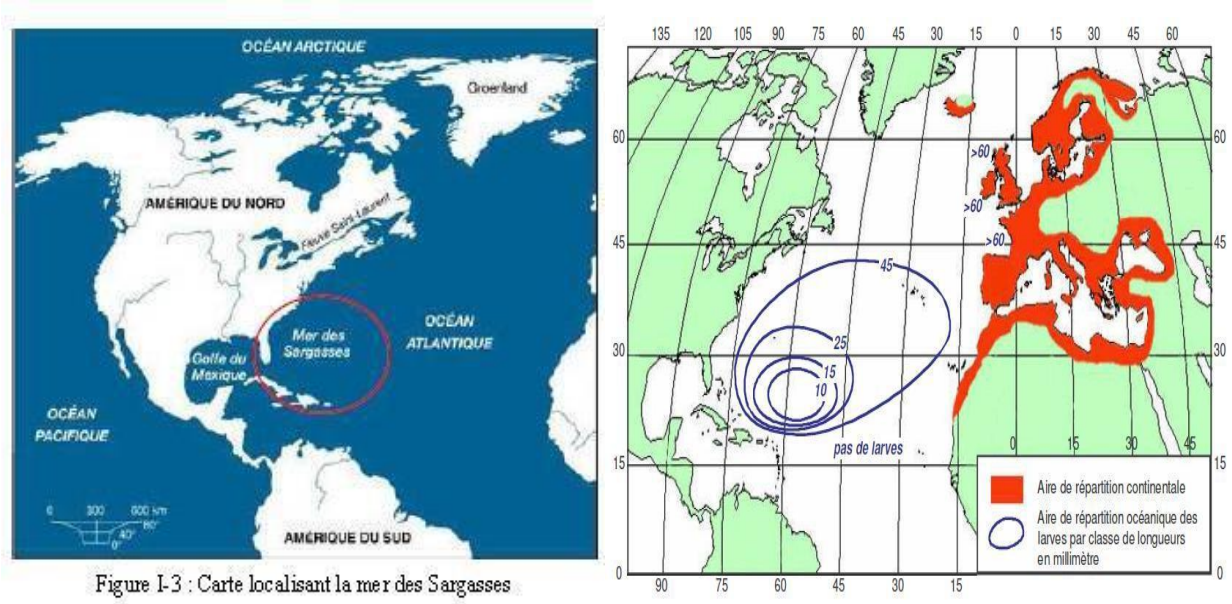

Figure 12: Distribution area of the European eel (*Anguilla anguilla* L., 1758), adapted from Germain (1927).

Chapter 3: Behavior of the European Eel (*Anguilla anguilla*)

1. Biorhythm:

The European eel (*Anguilla anguilla*) exhibits distinct biorhythms, particularly during its migratory and daily activity cycles. Throughout their extensive spawning migration to the Sargasso Sea, eels engage in diel vertical migration: they remain in deeper waters during daylight hours and ascend to shallower depths at night, likely to evade predators and optimize environmental conditions. Most eels initiate their oceanic migration between August and December, with their movements closely aligned with seasonal and daily light variations. These biorhythms are also reflected in their feeding and resting patterns, as eels are generally nocturnal, displaying increased activity at night and seeking shelter during the day. Migration and spawning timing is synchronized with environmental cues such as temperature and photoperiod, ensuring arrival at the Sargasso Sea under optimal reproductive conditions. This synchronization is vital for their survival and reproductive success, aligning their life cycle with favorable oceanic and continental factors. The European eel's dependence on these natural rhythms renders it particularly vulnerable to environmental disturbances, such as artificial lighting or climate change, which may disrupt migration timing and success(Miller et al., 2019; Righton et al., 2016).

2. Habitat use and plasticity

The European eel (Anguilla anguilla) is highly adaptable, occupying a wide range of habitats including freshwater rivers and lakes, brackish estuaries, and coastal marine zones, reflecting its remarkable ecological plasticity. This species is euryhaline, meaning it can tolerate and thrive across broad salinity gradients, and individuals may remain resident in one habitat type or shift between habitats during their growth phase(Daverat et al., 2006; Enbody et al., 2021; Rohtla et al., 2022). Genetic research indicates that European eels (*Anguilla anguilla*) constitute a single panmictic population, lacking local genetic differentiation. Their capacity to inhabit diverse environments is thus attributed to phenotypic plasticity—adaptive physiological and behavioral flexibility in response to local conditions rather than genetic variation (Enbody et al., 2021). During the yellow eel stage, many individuals exhibit high site fidelity, often remaining in the same habitat for years, but some may migrate within or between systems, influenced by factors such as food availability and habitat productivity (Capoccioni

et al., 2014). rowth rates and body condition can vary depending on habitat type, with marine and brackish residents often growing faster than freshwater residents, and local environmental conditions—such as prey availability—playing a key role in shaping these patterns (Capoccioni et al., 2014; Denis et al., 2023; Rohtla et al., 2022) . This plasticity in habitat use and movement allows the European eel to exploit a wide range of ecological niches and buffer against environmental changes, but also means that local management strategies must account for this variability (Daverat et al., 2006; Enbody et al., 2021; Rohtla et al., 2022).

3. Nocturnal and Cryptic Behavior

European eels are predominantly nocturnal, with their activity patterns strongly influenced by environmental cues, particularly darkness. During daylight, they remain hidden under rocks, in mud, or among aquatic vegetation to avoid predators and unfavorable conditions. Their nocturnal foraging intensifies during warmer months, accompanied by an expansion of their home range (Verhelst et al., 2018; Bašić et al., 2019). Activity levels are modulated by variables such as water temperature, lunar phase, and light availability, with peak activity typically occurring during the darkest periods. Some individuals show crepuscular behavior, being more active at dawn and dusk, while others remain strictly nocturnal (Barry et al., 2016; Bašić et al., 2019).

In freshwater and estuarine habitats, eels exhibit strong site fidelity, frequently returning to the same shelters after nightly foraging. Their movements are highly sensitive to artificial light, often avoiding illuminated areas, which highlights the importance of natural light regimes in shaping their behavior (Walker et al., 2014; Verhelst et al., 2018). This cryptic and light-avoiding lifestyle reduces predation risk and increases foraging efficiency, while also complicating efforts to observe them in natural settings (Barry et al., 2016; Bašić et al., 2019).

Being primarily nocturnal, the movements and activity patterns of European eels (Anguilla anguilla) are closely linked to environmental cues, particularly darkness. During daylight hours, they typically seek refuge under rocks, in mud, or among submerged vegetation to avoid predators and unfavorable weather conditions. At night—especially in warmer seasons—they emerge to forage, showing increased activity levels and expanded home ranges (Verhelst et al., 2018; Bašić et al., 2019). This nocturnal behavior is modulated by factors such as water temperature, lunar phase, and ambient light, with peak activity generally occurring during the darkest periods. Individual variation is also observed, as some eels are more active during crepuscular periods (dawn and dusk), while others are strictly nocturnal(Barry et al. 2016;

Bašić et al. 2019) .

4. Feeding Behavior

The European eel (*Anguilla anguilla*) exhibits substantial variation in its food patterns throughout its life cycle. Eels in the Sargasso Sea predominantly consume tiny, soft, gelatinous plankton, including Hydrozoa, during their earliest larval stage (leptocephalus), which corresponds with their small gape size and weak biting force (Bouilliart et al. 2015; Ayala et al. 2018). Their diet is initially limited to detritus and small benthic invertebrates as they transition into glass eels and migrate into estuaries. However, as the season progresses, it expands to include a variety of planktonic and benthic organisms, with crustacean plankton becoming especially significant (Wichelen et al. 2022). Once settled in freshwater or brackish habitats as yellow eels, their diet shifts to larger prey such as malacostracan crustaceans and fish, with the specific composition influenced by habitat type and prey availability (Denis et al. 2022). During the transition to the silver eel stage, which prepares them for their spawning migration, feeding generally ceases as they rely on stored energy reserves accumulated during the yellow eel phase (Parzanini et al. 2021). This ontogenetic dietary shift—from gelatinous plankton in the oceanic larval stage, to detritus and invertebrates as glass eels, to larger prey as yellow eels, and finally to fasting as silver eels—reflects the eel's remarkable adaptability and complex life cycle (Bouilliart et al. 2015; Wichelen et al. 2022; Denis et al. 2022; Parzanini et al. 2021).

The European eel's leptocephalus stage is distinguished from most fish larvae by its peculiar feeding technique. Instead of feeding on zooplankton, leptocephali mostly consume marine snow, which consists of collections of particulate organic debris that include bacteria, protozoans, detritus, and zooplankton fecal pellets (Kume et al. 2025; Miller et al. 2013; Tsukamoto et Miller 2020). Instead of actively selecting particular prey, studies reveal that these larvae graze non-selectively on particles floating in the water column, and the contents of their guts frequently match the composition of the marine snow that is accessible (Kume et al. 2025; Miller et al. 2013). They can only consume tiny, soft, or gelatinous particles due to morphological characteristics, including their soft jaws and minimal biting power, which is consistent with their reported diet (Bouilliart et al. 2015). This feeding behavior allows leptocephali to exploit a food source that is abundant but not heavily competed for by other fish larvae, supporting their growth and survival during their long oceanic migration (Tsukamoto et Miller 2020).

Upon reaching estuarine habitats, European glass eels (*Anguilla anguilla*) resume feeding following a fasting period associated with metamorphosis. Initially, only a small proportion of early-arriving individuals begin to feed, primarily consuming detritus and small benthic invertebrates resembling worms. As the migration season advances, feeding activity becomes more widespread, with all individuals eventually engaging in foraging. Their diet gradually diversifies to include a broad spectrum of both planktonic and benthic prey. Crustacean plankton—especially cyclopoid copepods—constitute a major dietary component, whereas benthic oligochaetes, though abundant in sediments, are ingested less frequently. This opportunistic and adaptable feeding strategy enables glass eels to cope with the fluctuating and often anthropogenically altered conditions encountered during their vital transition from marine to freshwater ecosystems (Wichelen et al. 2022).

In the yellow eel stage, *Anguilla anguilla* exhibits a highly adaptable and opportunistic feeding strategy, with its diet closely influenced by habitat characteristics and prey availability. Within estuarine systems, yellow eels predominantly consume malacostracan crustaceans such as *Gammarus zaddachi* and the green crab (*Carcinus maenas*), alongside fish prey including juvenile European flounder and, occasionally, conspecifics. The composition of their diet varies along the salinity gradient: crustaceans tend to dominate in larger estuaries, whereas fish are more frequently consumed in smaller systems. Stable isotope analyses support the observation that yellow eels exploit a broad spectrum of trophic resources, reflecting the ecological heterogeneity of their habitats. This trophic plasticity enables them to inhabit both brackish and freshwater environments successfully. Notably, feeding patterns are shaped more by local environmental conditions and prey distribution than by seasonal variation or individual eel size (Denis et al. 2022).

European eels often stop eating during the transition to the silver eel stage as they undergo major physiological changes in preparation for their lengthy spawning voyage. During their previous yellow eel phase, silver eels build up significant energy stores, mainly stored as lipids, which they now use instead of foraging. These energy reserves are essential since silver eels do not eat when migrating to the Sargasso Sea, and the buildup of certain fatty acids and total lipid content in their tissues is indicative of this preparation stage. Later-stage eels' higher levels of monounsaturated fatty acids and total lipid content lend credence to the theory that energy storage, not continuous feeding, is a crucial adaptation for migration and reproduction (Parzanini et al. 2021).

5. Silvering of physiological and morphological features:

Silvering in European eels marks the transformation from the yellow eel to the migratory silver eel stage, involving dramatic physiological and morphological changes. These include enlargement of the eyes, darkening of the dorsal surface, silvery coloration on the flanks, degeneration of the digestive system, development of the gonads, and a significant increase in fat stores. The process is tightly regulated by hormonal changes, particularly a sharp rise in 11-ketotestosterone, which is triggered by environmental cues such as decreasing water temperatures in autumn. After silvering, eels stop feeding entirely and begin their long spawning migration to the Sargasso Sea, relying solely on stored energy reserves. This migration is semelparous, meaning eels spawn once and then die. The silvering process and subsequent migration are essential adaptations for successful reproduction, ensuring that eels are physiologically prepared for the demanding journey and spawning event(Sudo & Yada, 2022)

The eyes of European eels develop significantly during silvering, a crucial adaptation for their impending oceanic migration. Silver-stage eels have a far higher average eye height than yellow-stage eels, according to morphometric research, and measurements suggest that this height increases dramatically when the eels enter the migratory phase. This expansion is believed to improve visual sensitivity in the deep-sea, low-light conditions the eels would eventually experience on their voyage. Hormonal changes are intimately associated with the increase in eye size, especially an increase in 11-ketotestosterone, which has been experimentally demonstrated to cause eye growth and other silvering-related alterations. For survival and navigation throughout the long-distance spawning journey to the Sargasso Sea, these morphological adaptations—including the bigger eyes—are thought to be crucial(Demirci, 2024).

Eels' olfactory systems change significantly during silvering, which probably helps them with their migratory and reproductive habits. When European eels go from the yellow to the silver stage, dopamine and its metabolite DOPAC rise dramatically in the olfactory bulb by 80% and 122%, respectively. This suggests that the eels have increased olfactory processing and may be more sensitive to environmental cues that are crucial for migration(Giorgi et al., 1994) With 90–100 flat radial lamellae and a wide variety of olfactory receptor cells, such as ciliated, microvillous, rod-tipped, and crypt cells, supported by specialized non-sensory cells and mucus-secreting goblet cells, silver eels have highly developed olfactory organs, according to morphological studies. These organs collectively improve odor detection and processing(Al-

Zahaby et al., 2024). The density and intricacy of dendritic spines on granule cells in the olfactory bulb increase at the cellular level during migratory phases, suggesting increased synaptic plasticity and a greater ability to process olfactory information. This may be important for long-distance migration orientation and navigation(Porceddu et al., 2022). These adaptations underscore the critical role of olfaction in eel migration, enabling them to detect and respond to environmental cues necessary for successful spawning journeys(Al-Zahaby et al., 2024; Giorgi et al., 1994; Porceddu et al., 2022)

During silvering, European eels (*Anguilla anguilla*) undergo distinct morphological changes, including the development of a darkened dorsal surface and silvery flanks—a transformation referred to as countershading. This coloration pattern is common among aquatic animals and functions as an effective form of camouflage, enabling eels to blend into their environment and avoid predation during their oceanic migration. The dark dorsal region minimizes visibility from above, while the reflective silvery flanks help the eel remain inconspicuous from the side and below by mirroring ambient light. In teleosts, such pigmentation changes are typically mediated by the redistribution and enhanced activity of pigment cells (chromatophores), with melanophores contributing to dorsal darkening and iridophores to lateral reflectivity. These physiological modifications are believed to be triggered by environmental cues and endocrine signals associated with the initiation of migration, optimizing the eel's concealment in open water habitats(Kelley & Merilaita, 2015).

European eels (*Anguilla anguilla*) undergo a progressive degeneration of the digestive system as they transition toward their migratory phase. This process is characterized by a gradual reduction in intestinal tissues and a marked decrease in the overall size of the gastrointestinal tract. Histological studies in closely related American eels have demonstrated significant declines in total intestinal area, muscle thickness, and villi surface area, accompanied by a reduction in gastrointestinal weight relative to body weight. These changes primarily result from atrophy, wherein cells diminish in size rather than undergoing cell death, and are most pronounced in the advanced stages of metamorphosis. The degeneration of the digestive system reflects a physiological shift from active feeding to complete dependence on previously accumulated energy reserves, supporting the prolonged migratory journey and subsequent reproductive effort (Lisi, 2018).

The digestive tract gradually deteriorates in European eels (*Anguilla anguilla*) as they start to prepare for their migratory period. The intestinal tissues gradually shrink throughout this

process, and the total size of the gastrointestinal tract noticeably decreases as well. In closely related American eels, histological investigations have revealed a decrease in gastrointestinal weight in relation to body weight, as well as notable decreases in total intestine area, muscle thickness, and villi surface area. Most noticeable in the latter phases of metamorphosis, these alterations are primarily caused by atrophy, in which cells contract rather than die. When the digestive tract degenerates, the body transitions from active (Sudo & Yada, 2022) eating to total dependence on stored energy, allowing for the prolonged migration and subsequent reproduction (Thillart et al., 2007).

European eels have significant endocrine changes during silvering, which primes them for migration and procreation. Strong gonadotropic axis activation is the most noticeable change, with notable increases in pituitary follicle-stimulating hormone (FSH) and luteinizing hormone (LH) as well as a sharp increase in the androgen 11-ketotestosterone (11-KT). This is believed to be the cause of many of the behavioral and physical changes linked to silvering, including increased migratory drive and enlarged eyes (Aroua et al., 2006; Rohr et al., 2001; Sudo & Yada, 2022). In contrast, the somatotropic (growth hormone) and thyrotropic (thyroid hormone) axes show little or no activation during this period, indicating these hormones are not central to the silvering process(Aroua et al., 2006) experimental studies have shown that administering 11-KT to immature eels can induce key silvering-related changes, confirming its pivotal role in this transformation(Rohr et al., 2001) Overall, these endocrine changes orchestrate the transformation from a sedentary yellow eel to a migratory, sexually maturing silver eel, ensuring that the individual is physiologically prepared for its prolonged oceanic journey and eventual spawning(Aroua et al., 2006; Sudo & Yada, 2022).

The immune system of European eels (*Anguilla anguilla*) undergoes notable changes, particularly in the swimbladder tissue. Transcriptomic analyses reveal that the expression of many immune-related genes is significantly modified at the silvering stage, with alterations in genes involved in immune response, protein metabolism, cell cycle, and apoptosis, suggesting increased cell turnover as the swimbladder adapts for migration. However, when silver eels are infected with the nematode *Anguillicola crassus*, the immune response in the swimbladder is much less pronounced compared to yellow eels, possibly because the energy demands associated with silvering limit the eel's capacity to mount a strong immune defense. In infected silver eels, there is a marked increase in the expression of mucin genes, indicating enhanced mucus production as a defense mechanism, but overall, the immune system appears less responsive to infection at this stage. This reduced immune reactivity may render silver eels

more vulnerable to pathogens during migration, potentially impairing swimbladder function and affecting their ability to complete spawning migration successfully.(Pelster et al., 2016; Schneebauer et al., 2017).

European eels have significant metabolic and cardiovascular changes during silvering, which primes them for their protracted spawning journey. One important adaptation is the red muscle's enhanced capacity to handle oxidative stress: silver eels exhibit a markedly lower level of lipid peroxidation than yellow eels, suggesting superior defense against damage from reactive oxygen species (ROS) produced during prolonged swimming and elevated aerobic metabolism(Amérand et al. 2017) Additionally, the size of respiratory muscles increases significantly during silvering, which likely enhances oxygen uptake and supports efficient migration through deep, low-oxygen environments .(Baan et al., 2020) Blood parameters also shift, with increased levels of cortisol observed in silver eels, which helps mobilize energy stores for both migratory activity and gonadal growth(Balm et al., 2007) The energy needs of migration are further supported by morphological changes such as increased body fat and protein content and liver enlargement (hepatosomatic index) (Balm et al., 2007; Demirci, 2024). Collectively, these cardiovascular and metabolic adjustments ensure that silver eels are physiologically equipped to undertake their long, energy-intensive journey to spawning grounds

6. **Environmental Sensitivity:**

Photoperiod is recognized as a primary environmental cue initiating downstream migration and the onset of silvering in European eels (*Anguilla anguilla*). Long-term monitoring in European river systems has demonstrated a strong correlation between decreasing day length and the timing of silver eel migration, which typically commences in late summer or early autumn. This photoperiodic control ensures temporal synchronization across individuals, enabling eels to begin their oceanic journey at an optimal time for successful arrival at their remote spawning grounds in the Sargasso Sea. Seasonal reduction in daylight not only triggers behavioral migration responses but also induces key physiological transformations associated with silvering. Although other abiotic factors—such as river discharge, lunar phase, and temperature—modulate the intensity and daily patterns of migration, the photoperiodic signal remains the principal driver of its initiation(Sandlund et al., 2017). photoperiod and clock genes: Photoperiod, or day duration, not only promotes migration but also regulates the

expression of clock genes in eels. According to research, several clock genes in the retina and hypothalamus (such Per3 and Cry4) exhibit daily oscillations during short photoperiods, but similar rhythms do not occur during long photoperiods. According to this, eels' internal biological clock is synchronized by variations in day duration, which helps them get ready for migration and other seasonal activities(Sudo et al., 2017). River discharge and tidal cycles constitute major environmental drivers influencing the timing and dynamics of downstream migration in silver eels (*Anguilla anguilla*). Long-term observational data from European rivers indicate that elevated and rising water levels—particularly in late summer and autumn—are strongly correlated with the onset and intensity of migration events. These hydrological cues not only synchronize migratory behavior among individuals but also likely reduce predation risk, as eels tend to migrate under safer conditions such as high water and moonless nights. The initiation of migration appears to be especially responsive to river discharge patterns in August, while short-term variations in migratory flux are modulated by both river level fluctuations and lunar phase. This adaptive synchronization optimizes survival and facilitates successful seaward migration, underscoring the critical ecological role of river hydrology and tidal dynamics in the life history of the European eel(Sandlund et al., 2017). Barriers, pollution, and climate change: Eel migratory and feeding habits are disrupted by human-induced factors including pollution, physical impediments (such dams and weirs), and climate change. While obstacles in rivers can obstruct or delay migratory pathways, lowering the number of eels that successfully reach breeding or feeding sites, pollution can deteriorate water quality, impacting eel health and navigational skills. River temperatures and flow patterns are changed by climate change, which can affect the timing of migration and decrease the suitability of habitat, thereby endangering eel populations (Boardman et al., 2024).

One important environmental factor affecting eel migration at various stages of life is temperature. The timing and success of migration are influenced by river and ocean temperatures for both European and Japanese eels. However, climate change has caused river temperatures to rise during migration periods, creating a discrepancy between ideal and actual conditions and possibly endangering eel populations. Normally, silver eels start their downstream migration when river temperatures fall within a preferred range of roughly 10 to 20°C, frequently in conjunction with high water discharge(Arevalo et al., 2021; Boardman et al., 2024). According to otolith stable isotope studies, larval eels encounter different temperatures in the ocean along their migration routes, with colder water temperatures at higher latitudes and later recruitment times (Gutiérrez-Estrada et Pulido-Calvo 2023; Kuroki et al.

2025).

Eels also exhibit vertical migration behaviors that are limited by water temperature, generally avoiding depths where temperatures drop below 4°C (Abe et al., 2023; Manabe et al., 2023). Water temperatures between 12 and 20°C are ideal for glass eels migrating upstream, while temperatures outside of this range can prevent migration, which raises questions about how global warming may affect recruitment (August & Hicks, 2007; Schabetsberger et al., 2016). Additionally, spawning tends to occur at oceanic temperatures between 16 and 24°C, and eels use their acute sensory abilities to detect these hydrographic features as navigational cues (Schabetsberger et al., 2016). Overall, temperature not only acts as a trigger for migration but also determines the physiological performance and survival of eels throughout their complex life cycle(Pohlmann et al., 2023).

Chapter 4: European Eel Diseases:

Numerous diseases pose a significant threat to European eel (*Anguilla anguilla*) populations, contributing substantially to their decline throughout the continent. Viruses that may cause hemorrhagic illness and increased mortality in both wild and farmed eels, such as Anguillid herpesvirus 1 (AngHV1), eel virus European X (EVEX), and aquabirnavirus EVE, are among the most significant diseases (Beurden et al. 2012; Ybáñez et al. 2023; Danne et al. 2022). *acterial* infections, including those caused by *Flavobacterium psychrophilum* and *Streptococcus iniae*, have been reported in wild and aquaculture settings, sometimes leading to outbreaks with high mortality rates (Pirollo et al., 2023b; Soares et al., 2019). Additionally common are parasitic infections, of which the invasive swim bladder nematode *Anguillicoloïdes crassus* is especially harmful; in certain areas, its prevalence can surpass 70%, and it is linked to weakened health and decreased migratory fitness (Ybáñez et al. 2023; Unger et al. 2024; Kantzoura et al. 2025).

Environmental stressors, such as pollution, may reduce eel immune responses and increase susceptibility to infection, thereby worsening the impact of these diseases.

Susceptibility to infection, and consequently the severity of disease impacts, is influenced by multiple environmental and biological factors. In their native habitats, diseases affecting European eels (*Anguilla anguilla*) are complex and highly variable. Accurate monitoring and assessment of disease prevalence in the wild are particularly challenging due to fluctuations across habitats, seasons, and eel life stages. For instance, viral infections such as Anguillid herpesvirus 1 (AngHV1) are more frequently reported in larger individuals, at inland freshwater sites, and during the summer or winter months. In contrast, the invasive swim bladder nematode *Anguillicoloides crassus* can reach prevalence levels as high as 70% in some regions, particularly among smaller eels, at brackish or coastal sites, and during the autumn season (Ybáñez et al., 2023).

Because native parasites and their eel hosts have co-evolved over long periods, their interactions are generally balanced and rarely lead to severe pathological effects. However, non-native parasites such as *A. crassus*, introduced via aquaculture and translocation practices, can cause substantial tissue damage, compromised health, and reduced migratory capacity—particularly during the early stages of invasion, when the host species lacks evolved defenses (Unger et al., 2024). The initial impacts of these exotic parasites tend to be significantly more severe than those caused by native parasites. Nevertheless, over time, partial adaptation may occur, leading to a reduction in parasite intensity and a more stable host-parasite equilibrium

(Unger et al., 2024; Ybáñez et al., 2023).

1. VIRAL DISEASES:

Several serious viral infections, including Anguillid herpesvirus 1 (AngHV1), Eel Virus European X (EVEX), and Eel Virus European (EVE), attack European eels. The most prevalent virus found in both wild and farmed eels is AngHV1, which usually causes hemorrhagic disease and higher mortality, particularly in larger individuals and at inland sites. Environmental factors, such as pollution and water temperature, can affect the virus's prevalence (Beurden et al., 2012). EVEX and EVE are also pathogenic, causing nonspecific hemorrhagic symptoms and contributing to disease outbreaks, particularly in glass eels and farmed populations, though they are less frequently detected than AngHV1(Beurden et al., 2012; Danne et al., 2022) Recent studies have also identified a novel virus, eel picornavirus 1 (EPV-1), in wild populations, but its full impact is still being investigated (Danne et al., 2021) he spread of these viruses is a major concern for both wild stocks and aquaculture, as stocking programs can inadvertently introduce or amplify infections if not carefully managed (Danne et al., 2022).

1.1 The rhabdovirus X (EVEX):

The rhabdovirus known as Eel Virus European X (EVEX) was initially identified in infected European eels in Japan in the late 1970s. Since then, it has been found in both wild and farmed eels across Europe and other areas. 1. EVEX encodes five classical structural proteins and a putative C protein, according to genomic studies, indicating some distinct genetic traits. It is closely related to the Vesiculovirus genus.(Galinier et al., 2012) . it was first observed in Europe in 1977 and has since been reported in several European countries, including Denmark, England, France, Sweden, the Netherlands, and Italy, as well as in North Africa, specifically Morocco (Jørgensen et al. 1994; Van Ginneken et al. 2004) In France, EVEX has primarily been detected in glass eels, especially in the Loire estuary and the Mediterranean region(Jørgensen et al. 1994).

According to recent studies, homologous recombination was crucial to the development of EVEX, resulting in the appearance of a dominant recombinant genotype almost half a century ago. This may have enhanced the virus's flexibility and capacity to infect eels in a variety of

environmental settings(Kong et al., 2024). The spread of EVEX is facilitated by the movement and trade of eels, including illegal trade, which can introduce the virus to new regions and populations While Anguillid herpesvirus 1 is more frequently found, EVEX is still a worry since it can result in hemorrhagic illness and increase mortality, particularly in young or stressed eels(Galinier et al., 2012; Kong et al., 2024) the combination of EVEX infection with other stressors, such as pollution or co-infection with other pathogens, can further threaten eel health and population stability (Kong et al., 2024).

Eel Virus European X (EVEX) can infect European eels throughout various phases of development, such as juvenile glass eels, growing phase yellow eels, and migratory adult silver eels. While outbreaks and clinical disease are more frequently reported in younger or stressed eels, such as glass eels meant for aquaculture or restocking, EVEX has been found in both wild and farmed populations, and infections can occur at any stage of life (Danne et al., 2021, 2022). The virus causes nonspecific hemorrhagic disease, which can lead to increased mortality, reduced growth, and compromised health, particularly in glass eels and elvers, making these early stages especially vulnerable (Beurden et al., 2012; Danne et al., 2022) EVEX is less common in yellow and silver eels, but it can still cause health outbreaks, parti cularly when paired with other infections or stresses(Beurden et al., 2012; Danne et al., 2021). The movement and trade of glass eels for stocking purposes have been identified as a key route for the spread of EVEX, raising concerns about introducing the virus into new habitats and affecting the health of local eel populations(Danne et al., 2022) Overall, EVEX poses a risk throughout the eel's life cycle, with the greatest impact observed in the early developmental stages, potentially affecting recruitment, survival, and the long-term stability of European eel populations(Danne et al., 2021, 2022; Galinier et al., 2012).

By decreasing their swimming endurance and general fitness, which are critical for their long-distance voyage to the Sargasso Sea for spawning, EVEX infections can have a detrimental impact on European eels' migration. According to laboratory experiments that simulate migration, eels infected with viruses such as EVEX have trouble swimming for extended periods of time, which makes it more difficult for them to cover the thousands of kilometers needed for effective migration and reproduction(V. van Ginneken 2006).

This decreased swimming ability is probably the result of the infection's physiological stress and energy drain, which might impair the eels' capability to sustain the prolonged effort required for migration. Furthermore, silver eels—the migratory adult stage—can have their health further compromised by the presence of EVEX and other pathogens, which may result in decreased reproductive success and contribute to the decline of eel populations (Amilhat et

al., 2014). Overall, EVEX infection is considered a significant factor that can hinder the migration and spawning success of European eels, especially when combined with other stressors such as pollution and parasitism(Amilhat et al. 2014; V. van Ginneken 2006).

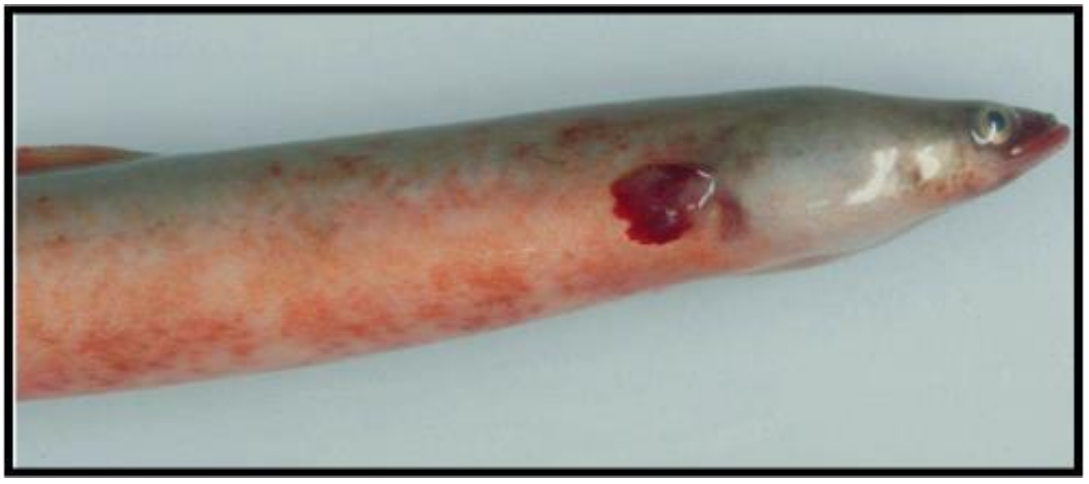

Figure 13: eel *Anguilla anguilla* with a HVA-infection. Hemorrhages in the skin, and severe hemorrhagic fins (Haenen et al., 2009)

2. BACTERIAL DISEASES:

A major cause of death for European eels, bacterial infections pose a danger to both aquaculture operations and wild populations. Rapid onset and high infection rates are characteristics of these illnesses, which frequently lead to major population decreases and financial losses. *Vibrio vulnificus, Flavobacterium psychrophilum, Edwardsiella anguillarum, and Streptococcus iniae* are the most prominent bacterial pathogens that impact European eels (Pirollo et al., 2023b).

2.1 *Aeromonas hydrophila*:

Aeromonas hydrophila is a highly virulent, opportunistic bacterium responsible for severe systemic infections in European eels, notably causing hemorrhagic septicemia and substantial mortality, particularly under aquaculture conditions. Transmission occurs primarily via contaminated water or direct contact, with outbreaks more frequent during warmer seasons. Experimental studies have demonstrated that *A. hydrophila* rapidly disseminates through the host, targeting multiple organs—especially the kidney—where it induces marked tissue necrosis and symptoms of septicemia. In response, the eel's immune system activates several key pathways, including the cytosolic DNA-sensing pathway and Toll-like receptor signaling,

leading to the production of antimicrobial peptides such as cathelicidins, which help inhibit bacterial proliferation. Despite these defense mechanisms, the bacterium's aggressive virulence often overwhelms the host, resulting in high mortality. Recent advances in vaccine development, particularly those targeting conserved outer membrane proteins of *A. hydrophila*, have shown promising results in enhancing immune responses and offering effective protection in farmed European eels. These findings represent important progress toward the prevention and control of *A. hydrophila* infections in eel aquaculture.(Esteve et al., 1993; He et al., 2019; Xiong et al., 2020).

In the early 1990s, *Aeromonas hydrophila*—a well-known pathogen of European eels (*Anguilla anguilla*)—was discovered to be a cause of illness in European farmed eels. It was connected to outbreaks of septicemia and ulcerative disease, especially during the spring and summer when water temperatures rise(Esteve et al., 1993). According to experimental infections, *A. hydrophila* may quickly kill eels, with the kidney being the main location of bacterial buildup and significant tissue destruction. The liver and gut also exhibit pathological alterations (Rui-zhang, 2011). According to recent research employing sophisticated RNA sequencing, infection sets off a robust immune response in the intestine, liver, and spleen of the eel. This response involves the activation of pathways, such as Toll-like receptors, and the synthesis of antimicrobial peptides, including cathelicidins, which aid in inhibiting bacterial growth (Xiong et al., 2020). These findings highlight the significant threat posed by *A. hydrophila* to European eel health and underscore the importance of monitoring and managing this pathogen in aquaculture settings(Rui-zhang, 2011; Xiong et al., 2020, 2021)

Although European eels (*Anguilla anguilla*) are afflicted by *Aeromonas hydrophila* at different stages of development, the majority of research concentrates on the yellow (juvenile/subadult) stage because it is the most vulnerable to infection. With notable immunological responses seen in the colon, liver, and spleen, including the activation of pathways like Toll-like receptors and the generation of antimicrobial peptides like cathelicidins, *A. hydrophila* can cause fast death at this stage(Xiong et al., 2020, 2021). In addition to seriously damaging kidney tissue, the bacteria also damages the liver and gut, resulting in organ malfunction and blood poisoning (Rui-zhang, 2011).

Farmed eels are especially vulnerable to outbreaks, which can happen through direct contact or waterborne transmission and are most frequent in the spring and summer when the water temperature is warmer (Esteve et al., 1993). The overall trend in aquaculture indicates that all life stages are at risk, with younger and stressed individuals maybe more vulnerable due to less established immune systems, notwithstanding the paucity of direct studies on the earliest larval

or glass eel stages. Immunization techniques have demonstrated potential in increasing immune responses and enhancing survival at various eel stages, including as vaccines based on outer membrane proteins(Feng et al., 2017; He et al., 2019, 2019). Overall, *A. hydrophila* poses a persistent threat throughout the eel's development, with the most severe impacts observed in juvenile and subadult stages commonly found in aquaculture (Esteve et al., 1993; Rui-zhang, 2011; Xiong et al., 2020, 2021).

2.2 Edwardsiella anguillarum:

Both wild and farmed populations of European eels are seriously threatened by *Edwardsiella* infections, which are mostly brought on by *Edwardsiella anguillarum, E. piscicida*, and *E. tarda.* Due to its high virulence, *E. anguillarum* frequently causes significant death rates by causing severe internal bleeding, liver damage, and blood clots in the hepatic arteries. According to recent transcriptomic research, *E. anguillarum* downregulates genes linked to metabolism and cellular maintenance during infection while upregulating genes involved in migration, colonization, biofilm formation, and communication (quorum sensing). The eel's immune system responds by activating a broad range of genes related to immunological defense, metabolism, and cell signaling. Certain host proteins, such STAT1 and ETS2, are essential for the defensive mechanism (Xiao et al., 2021). While *E. tarda* is more frequently isolated from freshwater and can potentially cause disease, E. piscicida is very pathogenic for eels and has been identified in both wild eels and natural environments, where it acts as a reservoir and has higher frequency at water temperatures above 20°C3. These bacteria's prevalence in the environment and in both healthy and sick eels emphasizes the possibility of epidemics, particularly in warm or stressful environments. Although identifying possible targets for vaccines and therapies is made easier by an understanding of the molecular relationships between *Edwardsiella* and its eel host, managing these infections is still a major issue for aquaculture and eel conservation.(Esteve & Alcaide, 2018; Xiao et al., 2021).

It affects European eels at all life stages, in both wild and aquaculture settings. E. piscicida has been isolated from diseased and healthy eels, as well as from freshwater environments, suggesting that both the eels and their habitats act as pathogen reservoirs. The prevalence in wild eel populations can reach up to 12%, with higher infection rates occurring during warmer months (above 20°C), which increases the likelihood of disease outbreaks (Esteve & Alcaide, 2018). Regardless of age, infected eels usually exhibit severe internal signs such hepatocyte

atrophy, liver hemorrhage, and blood clots in hepatic arteries, which, if left untreated, can result in a high death rate. Both wild and farmed animals may suffer large losses as a result of these illnesses, which interfere with vital physiological functions including metabolism and immunological response. Although the effects are more severe in young eels because they are more vulnerable to the disease's quick development, adults are still at danger, particularly when stressed or under unfavorable environmental circumstances. The fact that *Edwardsiella* is found in healthy eels raises the possibility of subclinical infections, which would enable the bacteria to survive in populations and cause illness when the right circumstances arise. In general, at every stage of development, *Edwardsiella* infections represent a continuous risk to eel health and population sustainability(Esteve & Alcaide, 2018; P. Lin et al., 2023; Xiao et al., 2021).

2.3. *Vibrio infections* **:**

Vibrio infections, particularly those caused by *Vibrio vulnificus*, have emerged as a significant threat to European eels (*Anguilla anguilla*). The first major outbreaks were reported in Spanish eel farms in 2000, followed by similar episodes in Denmark in 2004, where juvenile eels in freshwater systems experienced high mortality rates (Fouz et al., 2006). *V. vulnificus* is the causative agent of warm-water vibriosis, a rapidly progressing disease characterized by extensive hemorrhages in the head and gill regions, soft tissue necrosis, and death due to hemorrhagic septicemia. The bacterium primarily invades through the gills and secretes the RtxA1 toxin, which triggers an acute and atypical inflammatory response, often culminating in septic shock and rapid death (Callol, Pajuelo, et al., 2015; Callol, Reyes-Lopez, et al., 2015; Hernández-Cabanyero et al., 2023). Transcriptomic studies have shown that although the eel's immune system mounts an early localized response, the presence of RtxA1 is central to the pathogenesis and the high virulence observed. Moreover, *V. vulnificus* can persist in the aquatic environment and on the skin surface of eels for at least two weeks, suggesting that both the environment and infected individuals can act as reservoirs for the pathogen. Outbreaks are more likely to occur under conditions of elevated temperature and salinity, which enhance bacterial proliferation and transmission(Amaro et al., 1995).

Other Vibrio species, such as *V. furnissii* and *V. anguillarum*, have also been isolated from eels and shown to be pathogenic, causing similar symptoms and contributing to disease outbreaks in aquaculture(Conforto et al., 2021; Esteve et al., 1995) Co-infections with

parasites like *Gyrodactylus anguillae* can further increase eel vulnerability to Vibrio infections by providing additional entry points for the bacteria(Elgendy et al., 2016) The impact of Vibrio infections is seen at all life stages, but young eels are especially susceptible, often resulting in significant losses in both wild and farmed populations. Vaccination strategies, including cross-protective vaccines, have shown promise in reducing mortality, but controlling Vibrio infections remains a challenge due to the pathogen's environmental persistence and the rapid progression of disease(Fouz et al., 2006; He et al., 2019, 2020)

Infections with Vibrio can affect European eels in a number of ways, depending on the species and infection environment. With increased activity of immune enzymes like peroxidase and lysozyme and a strong mucosal immune response in the eel's skin, *Vibrio anguillarum* causes serious histopathological damage to the gills and liver, endangering the eel's health and increasing its vulnerability to secondary infections(Conforto et al., 2021). Additionally, co-infection with the parasite *Gyrodactylus anguillae* can increase eel vulnerability to V. vulnificus by providing entry points for the bacteria and acting as a mechanical vector, leading to more severe disease and higher mortality rates in affected populations(Elgendy et al., 2016)

- **Streptococcus:**

Streptococcus iniae is a major bacterial pathogen in aquaculture that has recently been identified as an emerging cause of disease in European eels (*Anguilla anguilla*). The first documented outbreak in this species occurred in Italy, where infected farmed eels exhibited clinical signs typical of streptococcosis, such as anorexia, lethargy, skin darkening, and petechial hemorrhages at the base of the fins and opercula. These symptoms frequently progressed to severe systemic infections, resulting in elevated mortality rates. The identification of *S. iniae* in European eels underscores the expanding host range of this pathogen. It raises concerns regarding its impact on eel health and the biosecurity of aquaculture operations(Pirollo et al., 2023b). Globally, *S. iniae* is known to cause significant losses in freshwater and marine fish, and its introduction into European eel farming underscores the increasing threat this species faces. In aquaculture settings, the illness may spread quickly, therefore early identification and care are essential to avoiding significant losses. The discovery of *S. iniae* in European eels emphasizes the necessity of close observation and enhanced biosecurity in eel farms to safeguard the viability of the industry and the health of the animals(Pirollo et al., 2023b; Weinstein et al., 1997). The first recorded outbreak of *Streptococcus iniae* infection in European eels (*Anguilla anguilla*) was reported in Italy in

2023. Prior to this, *S. iniae* was recognized as a significant pathogen in various wild and farmed fish species globally, but had not been associated with disease in European eels. During the Italian outbreak, affected farmed eels exhibited classical signs of streptococcosis, including anorexia, lethargy, skin darkening, and hemorrhages at the base of the fins and opercula, ultimately resulting in high mortality rates. This event demonstrated the susceptibility of *A. anguilla* to *S. iniae*, raising concerns for eel aquaculture due to the pathogen's capacity to cause rapid and severe disease outbreaks. The emergence of *S. iniae* in eel farming systems underscores the urgent need for early detection, stringent biosecurity protocols, and effective disease management strategies to safeguard animal health and ensure the sustainability of European eel production

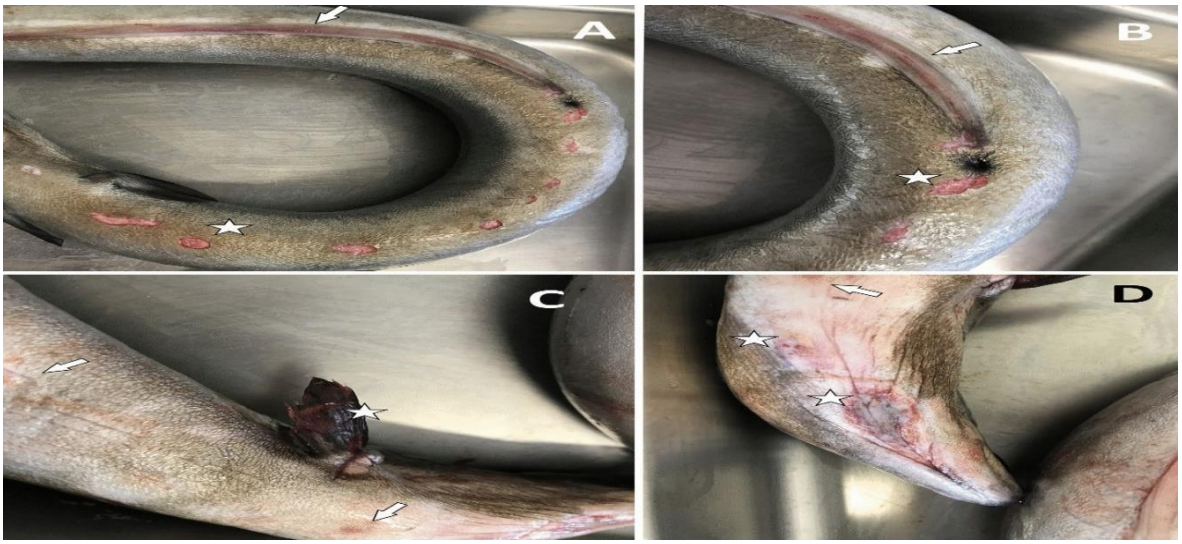

Figure 14: External examination of European eels (*Anguilla anguilla*) with *Streptococcus* infection (Pirollo et al., 2023a).

- **Flavobacterium:**

Flavobacterium psychrophilum was first isolated from moribund wild European eels (*Anguilla anguilla)* in Scotland in 2015, marking the initial report of this pathogen affecting eels in the wild. Infected eels displayed distinctive white patches on various parts of their bodies, and histological examination revealed lesions at the level of the integument, indicating that the bacterium primarily targets the skin and outer tissues. The presence of *F. psychrophilum* was confirmed through bacterial isolation and molecular methods, and whole-genome sequencing identified the isolates as belonging to sequence type 15 (ST15). While the full extent of its pathogenicity in eels is still under investigation, these infections are associated with visible morbidity and can contribute to mortality in wild populations, raising concerns about the health

of both eels and potentially cohabiting fish species(Soares et al., 2019) Additionally, *F. psychrophilum* is known for causing significant disease in other fish, such as salmonids, and its emergence in eels highlights the need for further research and monitoring to understand its impact and develop effective management strategies Furthermore, *F. psychrophilum* is known to cause serious illness in other species, including salmonids, and its appearance in eels emphasizes the necessity of more study and observation to fully comprehend its effects and create efficient management plans(Pavlin et al., 2025; Soares et al., 2019).

Flavobacterium psychrophilum has a notable impact on European eels, particularly in wild populations. The first documented cases in Scotland involved moribund eels displaying visible white patches on their bodies and lesions at the level of the skin and integument, indicating that the bacterium primarily targets outer tissues and can cause significant morbidity[1]. While the full pathogenicity in eels is still being studied, these infections are associated with increased mortality and may threaten local eel populations, especially if environmental conditions favor the spread of the bacterium.(Soares et al., 2019). *F. psychrophilum* has been implicated in high mortality rates, increased susceptibility to secondary infections, and significant financial losses in aquaculture because of the expenses associated with treatment and management in other fish species, including salmonids(Nematollahi et al., 2003). This pathogen's appearance in eels prompts worries about its potential to lead to comparable issues, including as population decreases and difficulties with conservation and fishery management. More investigation is required to completely comprehend the long-term impacts on eel health and to create efficient preventative and control measures (Nematollahi et al., 2003; Soares et al., 2019).

- ***Shewanella putrefaciens:***

Shewanella putrefaciens has recently emerged as a significant pathogen affecting European eels (*Anguilla anguilla*), particularly under hypoxic (low-oxygen) conditions. A notable outbreak was documented in L'Albufera Lake in Spain, where the prevalence of *S. putrefaciens* in wild eels increased markedly from 1.7% in 2008 to over 32% in 2014, coinciding with elevated water temperatures and reduced oxygen levels. Infected eels presented with clinical signs such as exophthalmia, ascites, oral lesions, foul odor, and characteristic white ulcers with red inflammatory margins. Necrotic lesions were commonly observed on the skin and gills, while affected spleens were frequently enlarged and pale. The bacterium was isolated from both diseased eels and freshwater samples, with environmental abundance increasing in parallel with hypoxia and temperature rise. Experimental infections confirmed the virulence of

S. putrefaciens, inducing significant mortality in eels and supporting waterborne transmission, especially under stressful environmental conditions. These findings emphasize the role of environmental stressors—particularly hypoxia and elevated temperatures—in precipitating outbreaks, and underscore the need for proactive water quality monitoring to mitigate the risk of shewanellosis in eel populations(Esteve et al., 2017). Under some circumstances, eels may withstand many parasitic infections with comparatively little biological cost; but, large parasite loads or co-infections can cause serious tissue damage, inflammation, and decreased health or survival, particularly in populations that are stressed or farmed(Warshafsky et al. 2019; Mayo-Hernández et al. 2015; Abdelmonem et al. 2009)

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3. PARASITIC DISEASES:

Parasitic diseases represent a major health concern for European eels (*Anguilla anguilla*), with the most impactful pathogens including the swimbladder nematode *Anguillicola crassus* and the gill monogeneans *Pseudodactylogyrus bini* and *P. anguillae* (Kennedy 2007; Køie 1991; Kirk 2003; Abdelmonem et al. 2009). Originally from Asia, *Anguillicola crassus* has spread widely among European eels, causing thickening and hemorrhaging of the swimbladder wall, which reduces its functionality and may hinder the eel's ability to migrate and reproduce (Kennedy 2007). This parasite is particularly problematic in warm, shallow lakes, where it may cause mass mortality. It is considered an efficient colonizer due to its ability to utilize a variety of intermediate and paratenic hosts (Unger et al. 2024; Kennedy 2007). Although often not lethal in their natural hosts, *Pseudodactylogyrus* species can cause significant local damage and economic losses in aquaculture settings when present in high numbers (Kennedy 2007; Køie 1991; Abdelmonem et al. 2009). Further notable parasites include zoonotic helminths such as *Anisakis* sp., nematodes (*Camallanus lacustris*, *Raphidascaris acus*), acanthocephalans (*Acanthocephalus lucii*), and cestodes (*Bothriocephalus claviceps*) (Dzido et al. 2020; Jabal et al. 2020). Although these parasites can be managed in aquaculture through drug treatments, controlling them in wild populations remains challenging (Kennedy 2007; Køie 1991; Kirk 2003).

3.1. Monogeneans:

Gill monogeneans, particularly *Pseudodactylogyrus anguillae* and *P. bini*, are ectoparasitic flatworms that infect European eels (*Anguilla anguilla*) at all life stages, from glass eels to fully grown adults. These parasites exhibit microhabitat preferences on the gill apparatus that vary with the size and developmental stage of the host, and postlarval migration within the gill structure has been documented (Buchmann 1989). Both species were introduced to Europe via the importation of live eels and have since established themselves in wild and farmed eel populations. Notably, European eels appear more susceptible to these parasites than their native hosts (Køie 1991).

Heavy infestations, especially under aquaculture conditions, result in substantial gill tissue damage, impaired respiration, decreased growth, and heightened vulnerability to secondary infections, which collectively lead to increased mortality and significant economic losses (Køie 1991; Slotved & Buchmann 1993). While initial infections can elicit a partial immune response, complete resistance does not occur, leaving eels susceptible to reinfection (Slotved & Buchmann 1993). The impact of gill monogeneans is particularly severe in intensive farming systems, where high stocking densities facilitate parasite transmission and exacerbate health risks (Køie 1991; Slotved & Buchmann 1993).

The prevalence of monogenean parasites in European eels (*Anguilla anguilla*) is strongly influenced by environmental factors, particularly habitat type and salinity. *Pseudodactylogyrus anguillae* and *P. bini* are more frequently encountered in freshwater and brackish environments, while their abundance tends to decrease in high-salinity (marine) habitats, likely due to their limited tolerance to saline conditions and their inability to complete their life cycle in such environments (Esposito et al., 2023; Jakob et al., 2009; Unger et al., 2024). Seasonal fluctuations also contribute to infection dynamics, with higher parasite loads often recorded during warmer months, possibly linked to increased host activity and elevated parasite reproduction rates (Esposito et al., 2023). Furthermore, habitat degradation, pollution, and the introduction of invasive species exacerbate the susceptibility of European eels to monogenean infections (Fazio et al., 2008; Hoste et al., 2025). The movement and restocking of eels between habitats can further facilitate the spread of these parasites, particularly when individuals are transferred from infested to previously uninfested waters (Køie, 1991). While larger and older eels may exhibit different infection patterns, environmental parameters such as water quality and salinity remain the principal factors governing monogenean prevalence. Understanding

these interactions is essential for the effective management of eel populations and for mitigating the impact of parasitic diseases on this critically endangered species (Esposito et al., 2023; Jakob et al., 2009; Unger et al., 2024).

3.2. Ichthyophthirius multifiliis:

Ichthyophthirius multifiliis is a ciliated protozoan parasite with a broad host range and global distribution, recognized as the causative agent of white spot disease in freshwater fish. Morphologically, it is characterized by its large, oval shape and the presence of numerous extrusomes—specialized organelles that facilitate host tissue invasion and contribute significantly to its pathogenicity (Yang et al., 2023). Molecular studies have shown that *I. multifiliis* isolates from different geographic regions can be distinguished using genetic markers, particularly the cytochrome c oxidase subunit I (COX-1) gene, which is effective in assessing genetic diversity and elucidating phylogenetic relationships among isolates (Li et al., 2022). These features—its specialized extrusome system and underlying genetic variability—help explain the parasite's adaptability and pathogenicity across diverse environmental conditions (Li et al., 2022).

The life cycle of *I. multifiliis* includes free-swimming infective stages, known as theronts, which rapidly locate and infect host fish, demonstrating high reproductive success under favorable conditions (McCallum, 1982). Surviving fish are capable of developing adaptive immunity, primarily through humoral antibodies that target parasite surface antigens and contribute to the expulsion of the parasite from host tissues (Jørgensen, 2017).

Ichthyophthiriosis, the disease caused by I. multifiliis, induces severe pathological changes in fish epithelial tissues, especially the skin and gills. Parasite invasion results in extensive tissue damage, including cellular necrosis, lysis, and epithelial desquamation, accompanied by marked inflammatory responses such as immune cell infiltration and granuloma formation(Ventura et Paperna 1985; Araújo et al. 2024). Infected fish frequently exhibit lamellar fusion, epithelial hyperplasia, and hyperaemia in the gills, significantly compromising respiratory function and overall physiological condition. The severity of epithelial damage escalates with repeated or heavy infections, often resulting in extensive tissue destruction and elevated mortality rates(Bu et al., 2025; Ventura & Paperna, 1985).

Ichthyophthirius multifiliis follows a direct transmission cycle, with reproduction occurring entirely outside the host. After feeding and maturing on the fish, adult parasites—referred to as trophonts—detach and encyst on environmental substrates, transforming into tomonts. Each

tomont is capable of producing between 200 and approximately 1,000 highly infective theronts, which are free-swimming stages measuring several tens of microns in length. These theronts are responsible for initiating new infections but have a limited environmental viability, surviving for only 1 to 2 days. Notably, theronts exhibit high sensitivity to salinity and are unable to survive at salinities exceeding 5 to 8‰, which constrains their distribution in brackish or marine environments(Yang et al., 2023).

Ichthyophthirius multifiliis can tolerate a wide temperature range, from 3°C to 28°C, with optimal development occurring between 16°C and 20°C. Elevated water temperatures significantly accelerate the parasite's life cycle; for instance, the complete cycle takes approximately 21 days at 10°C, but only 7 days at 25°C. Environmental conditions such as complex or uneven substrates, reduced water flow, accumulation of organic matter, and high fish densities—particularly near physical obstacles—further facilitate parasite proliferation. Salinity is also a critical limiting factor; values exceeding 8‰ markedly inhibit parasite development and reduce infection severity. Experimental studies have demonstrated that tomocyst formation and theront development can occur within a thermal window of 5°C to 30°C, with more rapid development and increased theront output observed at moderate temperatures, although both processes are strongly suppressed at salinities above 5–8‰(Aihua & Buchmann, 2001; Forwood et al., 2015).

3.3. Acanthocephalans:

Acanthocephalans such as *Pomphorhynchus laevis, Paratenuisentis ambiguus*, *Acanthocephalus clavula, A. lucii, and A. anguillae* are small, cylindrical or conical endoparasitic worms (5–30 mm long) characterized by a swollen anterior end equipped with a retractable, hook-covered proboscis for attachment to host tissues. These parasites are polyxenous, with adults inhabiting the intestines of fish, while their larval stages develop in crustacean intermediate hosts like amphipods (Gammarus) or isopods (asellus); the life cycle is completed when fish consume infected crustaceans. Molecular barcoding and morphological studies confirm the diversity of acanthocephalan species in European freshwater fish, and highlight the proboscis as a key diagnostic feature . Pathological observations show that attachment by the proboscis can cause significant damage to the fish's digestive tract, including tissue perforation and inflammation, especially with species like *Pomphorhynchus tereticollis*(Lewisch et al., 2020)

Acanthocephalans, such as *Acanthocephalus clavula*, are generally well tolerated by their fish hosts and rarely cause significant disease, except when present in high numbers. Typically, infections may result in mild digestive disturbances; however, heavy parasite burdens can impair intestinal transit and, in severe cases, lead to intestinal obstruction or even rupture—particularly when fish ingest large quantities of infected amphipods. These parasites are most frequently observed during winter and early spring and are commonly found in salmonid and cyprinid species across temperate regions. In European eels, A. clavula is a predominant acanthocephalan species, detected in both the intestinal tract and body cavity. It has also been reported in other freshwater fish species, including barbel, chub, roach, gudgeon, and trout. Although A. clavula is generally non-host-specific and exhibits low pathogenicity, high infection intensities can result in marked irritation or even perforation of the intestinal mucosa. Studies on European eels have documented widespread acanthocephalan infections, which typically exert limited effects on host condition unless parasite loads are particularly elevated(Gérard et al. 2013)

3.4. Myxosporidiosis:

Myxosporidiosis in fish, caused by *myxozoan* parasites such *as Myxidium, Myxobolus, Henneguya, Ceratomyxa,* and *Kudoa*, is well documented in both wild and farmed salmonids and cyprinids across various freshwater environments. These parasites are characterized by multicellular spores containing polar capsules and coiled polar filaments, and infections typically manifest as chronic granulomatous lesions. Clinical signs may include respiratory distress associated with whitish cysts on the gills, while *Myxobolus cerebralis* specifically causes nervous and skeletal abnormalities known as “whirling disease,” which can result in cartilage destruction, inner ear compression, and skeletal deformities. Histopathological analyses have confirmed that severe infections may induce significant tissue damage, growth retardation, and impaired respiratory function, although mild infections are often well tolerated by the host. Recent studies have provided detailed morphological and molecular identification of *M. cerebralis* in trout, including high-resolution descriptions of spores and associated lesions, and have extended the known geographic distribution of these parasites across North America (Ksepka et al., 2020; Ruiz et al., 2017).

In eels, which act as definitive hosts, myxosporidian parasites such as *Myxidium* release infective spores directly into the aquatic environment. These spores must subsequently be

ingested by an intermediate host, presumed to be a sedentary invertebrate—most likely a tubificid worm of the genus *Tubifex*. This indirect life cycle has been supported by both molecular and morphological studies, which have demonstrated that different myxosporean species infect specific tissues in eels and that successful transmission is influenced by environmental factors, including the availability and density of suitable invertebrate hosts and local water conditions. In European eels, the infection process and organ tropism of these parasites have been well documented, with evidence showing that multiple genetically distinct myxosporean species can infect various organs. Moreover, tissue specificity serves as an important diagnostic criterion for identifying these infections(Freeman & Kristmundsson, 2018).

A detailed account of *Myxidium giardi* pathology in European eels is provided in the study by Copland, which investigates histopathological changes in both wild and cultured specimens. The research revealed that lesions in the kidney and gills were typically mild; however, pronounced granulomatous responses were observed in organs such as the spleen, peritoneal fat, liver, and gas gland—particularly in young eels (elvers and fingerlings). The study further describes cyst formation and rupture, spore release, and evidence of vascular dissemination, emphasizing that severe pathology is predominantly associated with heavy infections. These findings underscore the importance of early detection and monitoring, especially in aquaculture settings, where young eels are highly susceptible (Copland, 1983). Another important reference is the work by Ventura and Paperna, which confirms that pathological damage is severe primarily in the kidneys of elvers, while older eels tend to develop tolerance to infection

3.5. Trichodinosis caused by Trichodina sp.:

Trichodinosis is a disease caused by Trichodina spp., ciliated protozoan parasites that attach to the skin and gills of fish, resulting in mechanical damage, increased mucus secretion, epithelial hyperplasia, and heightened susceptibility to secondary bacterial and viral infections. These ectoparasites are not host-specific and can infect a wide range of freshwater and marine fish species. In aquaculture, heavy infestations pose a serious threat, leading to respiratory distress, secondary infections, and substantial economic losses. The European eel (*Anguilla anguilla*), especially at the subadult and glass eel stages, is particularly vulnerable to *Trichodina* infections (Suresh et al., 2023; Kumar et al., 2021; Blazhekovikj-Dimovska &

Stojanovski, 2020).

Under favorable conditions, *Trichodina* spp. remain active at water temperatures above 5 °C, with peak abundance typically observed from late winter to early spring as temperatures rise above 10 °C. Prevalence tends to decline significantly from October to February. The severity of infection is strongly influenced by environmental factors such as water temperature, photoperiod, and fish stress due to overcrowding. In more severe cases, *Trichodina* spp. may even erode gill tissues or invade the nasal cavities, causing olfactory dysfunction.

Control and treatment strategies traditionally rely on chemicals such as copper sulfate, formalin, and sodium chloride. However, concerns persist regarding their long-term efficacy, safety, and ecological consequences. As an alternative, Chinese herbal medicines have garnered attention due to their low residual accumulation, minimal risk of resistance development, and reduced environmental impact. Although promising, the use of these natural compounds remains at an early stage and requires further validation to ensure both safety and therapeutic effectiveness (Si-s, 2014).

The presence and abundance of *Trichodina* spp. have also been strongly associated with degraded aquatic environments. Studies have demonstrated correlations exceeding 80% between *Trichodina* prevalence and poor water quality classifications, including elevated pollutant and organic matter levels. These findings support the use of *Trichodina* as a valuable bioindicator for monitoring aquatic habitat health. As such, tracking *Trichodina* spp. in fish populations provides critical insight into ecosystem conditions and serves as an effective early warning system for environmental degradation .(Biswas et al., 2023; Ogut & Palm, 2005)

2.6. Crustacean parasites:

Several species and genera of crustaceans are recognized as pathogenic parasites of the European eel (*Anguilla anguilla*) in both freshwater and brackish environments. Among the most commonly reported are the copepod *Ergasilus* sp. and the branchiuran *Argulus foliaceus*, which typically attach to the gills or skin, inducing tissue damage, irritation, and heightened vulnerability to secondary infections(Bakaria et al., 2018). The local crustacean community is intimately related to the variety and abundance of these crustacean parasites, and both environmental changes and the introduction of new crustacean species can have an impact(Sures & Streit, 2001). . In some regions, shifts in the composition of native and invasive crustacean fauna have led to changes in the parasite communities found in eels, highlighting the ecological connection between intermediate hosts and parasite transmission(Sures & Streit,

2001; Thielen et al., 2007)

The most common crustacean parasites, such as *Ergasilus* sp. and *Argulus foliaceus*, are recognized as pathogenic to European eels (*Anguilla anguilla*) in both freshwater and brackish environments, often attaching to the gills or skin and contributing to tissue damage, irritation, and increased susceptibility to secondary infections(Bakaria et al., 2018).

- ***Tracheliastes polycolpus***

is a copepod crustacean ectoparasite, typically measuring around 10 mm in length, that primarily infests freshwater cyprinid fish in temperate regions. It attaches permanently and deeply to the host's skin, muscles, or gills using specialized hooks, feeding predominantly on blood. This parasitism results in localized hemorrhages and inflammation, often progressing to skin ulceration and tissue necrosis. The damage caused can lead to secondary infections—both fungal and bacterial—as well as hemodilution and disturbances in the fish's osmoregulatory functions. The life cycle of *T. polycolpus* involves two larval stages: a free-swimming nauplius that develops into an infective copepodite, which then attaches to a host and matures into an adult. Environmental factors, particularly elevated water temperatures, are known to exacerbate both the prevalence and severity of infestations. The pathogenic impact varies according to host-related factors such as age and body size, and is further modulated by ecological conditions, with certain habitats showing heightened vulnerability under specific environmental pressures(Cardon et al., 2011).

- ***Lernaea cyprinacea***

is a copepod crustacean parasite characterized by a worm-like body and a distinctive anterior anchor that enables it to embed deeply into the tissues of its fish hosts, resulting in visible lesions and hemorrhages, particularly in estuarine sprat populations and European eels. Its optimal development occurs in freshwater at temperatures ranging from 14 to 32 °C, with peak infestations typically observed between April and November, especially in warm, lentic environments such as ponds. However, it is also commonly found in brackish coastal waters. In eels, *L. cyprinacea* often attaches to the lower jaw or inside the oral cavity, where its anchoring apparatus causes deep tissue damage and bleeding. Upon detachment, the parasite leaves open wounds that are highly susceptible to secondary infections, particularly bacterial and fungal, which generally pose a greater threat to host survival than the parasite itself. Medium-sized eels tend to be the most frequently affected, with infestations often leading to weakness and anorexia, although direct mortality caused by the parasite is rare. The infection

is typically multispecies, affecting various fish cohabiting the same environment, and host susceptibility is influenced by factors such as body size and environmental conditions(Ranjan et al., 2024).

- ***Paragnathia formica***

is a gnathiid isopod crustacean whose larval stages are hematophagous ectoparasites, primarily targeting fish species such as mullets, flounders, gobies, and eels in brackish environments. The larvae, typically measuring 2–5 mm, attach to the host for several hours to days, feeding on blood and inducing localized inflammation, anemia, weight loss, and reduced growth. While mortality is generally low, it may occur in the most vulnerable individuals. The life cycle begins in winter with the release of first-stage larvae (zuphea), which briefly parasitize fish before detaching and developing into second-stage larvae (praniza), and ultimately into non-feeding adults. All energy required for adult survival and reproduction is acquired during these brief parasitic larval stages(Tinsley & Reilly, 2002). Due to their lack of host specificity, *P. formica* larvae may infest a variety of fish species, with infestations occasionally including dozens of parasites per eel. The adults rely on the resources they have acquired during their parasitic larval phase and dwell in tunnels in saltmarshes without feeding. Although they are still poorly understood, the physiological impact on fish involves not only immediate tissue destruction but also the possibility of secondary infections and long-term physiological repercussions(Manship et al., 2012; Tinsley & Reilly, 2002).

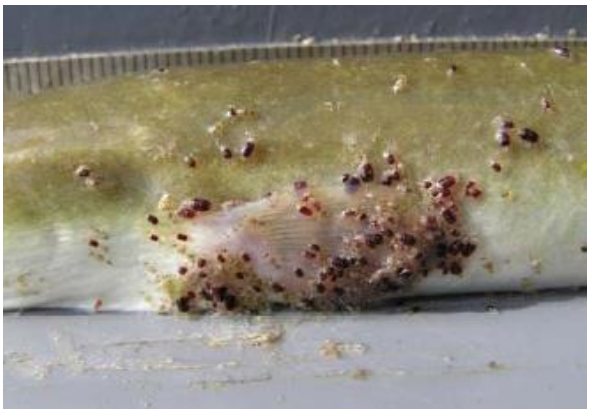

Figure 15: Presence of isolated *Paragnathia formica* individuals on the pectoral fin of a young eel (Elie, 2015)

Chapter 5. Growth and stock assessment of eels

The stock assessment of the European eel (*Anguilla anguilla*) presents significant challenges due to its panmictic population structure and extensive geographic distribution. Assessment methodologies applied across Europe are heterogeneous; some regions implement demographic models based on silver eel escapement monitoring, whereas others employ cohort-based approaches or spatial extrapolation techniques. A considerable proportion of these methods lack formal validation, which can result in substantial biases in stock size estimation and, consequently, elevate the risk of overexploitation or insufficient conservation actions (Höhne et al. 2024; Dekker 2000). To mitigate these issues, the International Council for the Exploration of the Sea (ICES) advocates for the integration of multiple assessment approaches—particularly the use of glass eel recruitment indices in conjunction with demographic models—within a standardized and scientifically validated framework.

Key Challenges and ICES Recommendations

- **Fragmented and Unstandardized Approaches** – Local assessments of European eel stocks exhibit significant variation in methodology and data quality, which results in inconsistent findings and increases management uncertainties. The International Council for the Exploration of the Sea (ICES) recommends the development of a standardized assessment toolbox accompanied by centralized quality control mechanisms (Höhne et al. 2024).
- **Bias from Stocking and Data Gaps** – The practice of stocking unmarked farmed eels introduces bias into age-based population models. At the same time, many habitats remain either unassessed or are monitored using unvalidated methodologies (Kullmann et al. 2018; Höhne et al. 2024).
- **Panmictic Population Considerations** – Given that the European eel constitutes a single panmictic breeding population, ICES emphasizes the need for assessments that integrate data across the species' entire distribution range, rather than relying solely on isolated local stock evaluations (Bornarel et al. 2018; Bornarel 2016; Dekker 2000b

Table 3: Main Stock Assessment Methods

Method/Model	Description & Use	Strengths	Limitations	Citations
Glass Eel Recruitment Indices (GEREM)	Uses time-series of glass eel (juvenile) recruitment at river mouths to estimate population trends at local, regional, and European scales.	Best for range-wide assessment; captures panmictic nature; supported by ICES.	Does not account for continental phase fragmentation; sensitive to local data gaps.	(Bornarel, 2016; Bornarel et al., 2018)
Demographic Models	Estimate escapement and biomass using life-stage or age-structured data, often incorporating local monitoring (e.g., silver eel counts).	Can be tailored to local conditions; useful for management targets.	Often overestimate escapement; require validation; sensitive to unmarked stocking.	(Kullmann et al. 2018; Höhne et al. 2024)
Cohort/Life-Stage Models	Simplified models based on life stage (not age/size), using available catch and recruitment data.	Adaptable to data-poor situations; provides preliminary stock estimates.	Relies on assumptions (e.g., stable recruitment); limited accuracy.	(Dekker, 2000)
Capture-Mark-Recapture & Telemetry	Used for local assessments, especially in restocking studies, to estimate survival and recruitment.	Accurate for cryptic or juvenile stocks; good for evaluating restocking.	Labor-intensive; limited to local scales.	(Desprez et al., 2013; Matondo et al., 2020)
Biomass Reference Points	Relate standing stock to environmental variables (e.g., nitrate levels) for catchment-specific management.	Useful for local management; can inform reference points.	Requires extensive local data; not always transferable.	(Bark et al., 2007)

1. Growth and age determination:

Accurate knowledge of eel growth rates is crucial for reliable population modeling and effective management, as growth parameters, such as length-at-age, directly inform stock assessment models used to estimate natural mortality, fishing mortality, and recruitment success. Research on both marine and freshwater eels consistently demonstrates that growth dynamics—shaped by factors including population density, habitat quality, and interspecific competition—have a significant influence on stock status and the effectiveness of management strategies(Barua et al., 2023; Newhard et al., 2021; Panfili et al., 2022; Pedersen et al., 2023; Wakiya et al., 2022). In this regard, estimating important metrics like spawning biomass, exploitation rates, and sustainable catch limits is made easier by length-based stock assessment techniques that employ growth factors derived from models like the von Bertalanffy Growth Function(Barua et al., 2023). Research demonstrates that growth rates can vary widely depending on environmental conditions and stocking density, with higher densities often leading to slower growth and reduced surviva(Pedersen et al., 2023; Wakiya et al., 2022). Mark-recapture and telemetry studies further reveal that growth rates are highly variable among individuals and habitats, complicating management but providing essential data for refining stock assessments(Newhard et al., 2021; Panfili et al., 2022) By understanding these growth processes, management authorities can better forecast the long-term sustainability of eel populations, refine stocking strategies, and establish appropriate size regulations (Barua et al., 2023; Félix et al., 2020; Matondo et al., 2020, 2021; Newhard et al., 2021). Recent studies estimating population dynamics, exploitation rates, and sustainable catch limits for eel species through length-based methods and growth parameters highlight the importance of incorporating robust growth data into stock assessment models. Such integration is essential for accurately evaluating eel stock status and ensuring effective conservation and fishery management(Barua et al., 2023).

❖ Age determination:

It is a critical aspect of biological and fisheries research, as it underpins growth modeling, population dynamics, and effective management strategies. In fish, age is most commonly estimated by analyzing calcified structures such as otoliths (ear stones), which display annual growth rings similar to those in trees, allowing researchers to infer age and growth rates over the lifespan. Accurate age determination is essential for constructing reliable growth models,

such as the von Bertalanffy growth function, and for estimating key parameters like longevity, mortality rates, and recruitment success. However, challenges remain, including the need for validation of age estimates and the potential for variation in growth ring formation due to environmental or physiological factors (Mesa & Eastman, 2023)

Age estimation in European eels primarily relies on the analysis of otoliths (ear stones), which exhibit annual growth rings that can be counted to determine age. The most commonly used techniques involve grinding, polishing, and staining the otoliths along the sagittal plane to enhance the visibility of these rings. Recent methodological improvements have led to more precise and generally higher age estimates compared to earlier approaches based on whole-otolith readings(Andrews et al., 2025; Durif et al., 2020).

The most widely used method for age estimation in teleost fishes, including the European eel, is **otolithometry**, owing to the ability of otoliths (ear stones) to record both annual and daily growth increments throughout the fish's life. Since the late 19th century, otoliths have been prepared and examined—either whole or after sectioning and staining—in order to count these growth rings and estimate age with good precision. In parallel, more recently, advances in otolith microchemistry have allowed researchers to analyze the elemental composition of otoliths, offering valuable insights into the environmental history and life cycle events of individual fish. Although these techniques can be both costly and time-consuming, they provide a powerful tool for reconstructing habitat use and migration patterns. As such, otoliths function not only as precise age indicators but also as sensitive recorders of ecological information, making them indispensable for both fisheries management and ecological research (Lecomte-Finiger, 1999; Correia, 2019).

The first discovery of using otoliths for age estimation in fish dates back to the late 19th century, with the pioneering work of Reibisch in 1899. Reibisch observed that otoliths, much like tree rings, contain visible growth increments corresponding to seasonal and annual cycles, enabling researchers to estimate a fish's age with reasonable precision. This foundational observation led to the establishment of otolithometry as a scientific discipline, which has since become a cornerstone of fisheries biology in age and growth studies. Over time, the method has been refined to include not only annual but also daily growth increments, significantly improving the resolution of life history reconstructions. Today, otolith analysis remains a standard and highly valued technique for age estimation in teleost fishes, including the European eel, due to its reliability and the detailed chronological information it provides(Martinsen et al., 2022).

Several structures can be used to estimate fish age, including scales, otoliths, fin rays, spines, and vertebrae. However, in anguillid eels such as Anguilla anguilla, scales are unsuitable for age estimation because they develop relatively late—only after several years, once the eel reaches a length of 16–20 cm in freshwater—thereby limiting their usefulness. Furthermore, not all scales form simultaneously, and their small size, deep subcutaneous position, and irregular annulus formation make them difficult to interpret. Vertebrae have received little attention in eel studies, likely due to their porous structure, which renders them unreliable for age determination. Consequently, otoliths remain the only structure currently used for age estimation in European eels. Ehrenbaum and Marukawa were the first to apply otolith analysis to Anguilla anguilla in the early 20th century, establishing it as the standard method for eel age determination(Güçlü et al. 2025; Lecomte-Finiger 1992)

- Description–Function:

The inner ear of a fish is a highly specialized organ with remarkable structural and functional diversity that supports both hearing and balance. It contains three primary otolith end organs: the saccule, utricle, and lagena. The utricle is primarily involved in balance and spatial orientation, while the saccule is mainly responsible for sound detection. The function of the lagena is less clearly understood, but it appears to assist in hearing, especially at higher sound intensities (Kay, 2023; Ladich & Schulz-Mirbach, 2016a). The otoliths move in response to sound waves, bending the hair cells in the sensory epithelia (maculae), which transmit information to the brain for processing in the vestibular or auditory systems (Kay, 2023; Nicolson, 2005). Additional hearing structures, such the connections between the swim bladder and the inner ear, can improve the sensitivity and frequency range of fish hearing by more efficiently transmitting sound vibrations(Nicolson, 2005). The variety in inner ear architecture, including otolith size and shape and sensory hair cell arrangement, reflects adaptations to various ecological settings and acoustic requirements.(Ladich & Schulz-Mirbach, 2016b; Popper et al., 1982) . Damage to hair cells, especially in the saccule and lagena, can impair hearing, but some redun(Kay, 2023). Overall, the structure and function of the fish inner ear are sculpted by evolutionary forces and habitat-specific requirements, making it a complex system that is precisely tuned for both sensing ambient noises and maintaining homeostasis(Kay, 2023; Ladich & Schulz-Mirbach, 2016b; Popper et al., 1982).

In osteichthyan fishes (bony fishes), the inner ear consists of three otic sacs—saccule, utricle, and lagena—each containing a distinct calcareous otolith: the sagitta, lapillus, and asteriscus,

respectively. These otoliths serve as mechanoreceptors, triggering the sensory hair cells (kinocilia) of the macula through their motion in response to sound waves and body acceleration. They are anchored above the macula by the otolithic membrane, which has a specialized structure: a gelatinous, reticulated zone overlying the sensory area, and a looser subcapular zone extending over both sensory and non-sensory regions. This structural arrangement is critical for efficient mechanoreception and balance. The system is filled with endolymph fluid, allowing otoliths to move in response to mechanical stimuli. In certain osteichthyan groups such as Ostariophysans, the swim bladder enhances the stimulation of the inner ear by sound. Otoliths also differ in size and shape across the three otic sacs, reflecting their distinct roles in auditory perception and equilibrium (Schulz-Mirbach et al., 2018a; Gauldie). The mass and shape of otoliths are critical factors that influence their movement and, consequently, affect the sensitivity and functional performance of the fish inner ear (Schulz-Mirbach et al., 2018).

Bony fishes' otoliths exhibit notable morphological variations that are indicative of both their developmental processes and evolutionary history (phylogeny), with notable variation seen both within and between species. Because these variations are influenced by both genetic and environmental variables, otolith morphology is a useful tool for taxonomic identification and for differentiating between populations or species that are closely related 12. Studies have shown, for instance, that otolith size and shape may accurately distinguish species within genera and even aid in the identification of cryptic or visually identical species(Zarei et al. 2023; D'Iglio et al. 2021)

This species-specific variation enables researchers to use otoliths in a range of practical applications, including the analysis of fish diets from stomach contents, the reconstruction of past environments and faunal assemblages from archaeological or paleontological sites, and the evaluation of geographic variation among fish populations or stocks (D'Iglio et al., 2021; Santos & Vaz-dos-Santos, 2022). As a result, otolith morphology is considered reliable and is frequently employed in fish taxonomy, ecology, and evolutionary studies(Zarei et al. 2023; D'Iglio et al. 2021)

❖ Composition:

Fish otoliths are composed mainly of aragonite, a crystalline form of calcium carbonate ($CaCO_3$), with a total organic matter content ranging from 0.2% to 10%. The organic matrix is primarily a high-molecular-weight protein rich in acidic amino acids, which facilitates the mineralization process by coordinating calcium ions and stabilizing the crystal structure. This proteinaceous matter is chemically uniform across different fish species, and the alternating layers of calcium carbonate and protein create a structure similar to an onion bulb. Isotopic analysis of otoliths can provide information about the fish's environmental history, such as water temperature and habitat type(Degens et al., 1969)

Fish otoliths exhibit multiple levels of temporal resolution in their growth structure. At the finest scale, primary increments are typically deposited on a daily basis, enabling age estimation with a precision of one day—although in some species, this daily pattern may be absent or difficult to discern. These daily rings can be observed under high magnification, with mineral-rich (L) zones appearing light and protein-rich (D) zones appearing dark; the thickness of these layers varies, with dark zones generally being thinner than light ones. At a broader scale, seasonal zones become visible, with opaque (dark) and translucent (light) bands corresponding to periods of slower and faster growth, respectively. These reflect both environmental and physiological changes occurring over several months. Finally, annual increments—sometimes visible to the naked eye—constitute a third level of resolution and are used to estimate the fish's age in years. These growth patterns in otoliths serve as valuable chronological records of individual life histories and environmental conditions(Panella, 1971)

❖ Application:

Pannella's discovery of daily growth increments in 1971 was a significant advancement in the use of otoliths to determine fish age, which had started in 1899 with Reibisch's detection of yearly rings (annuli). Since then, otolith microstructure analysis has emerged as a crucial technique for figuring out fish species' ages, growth rates, larval lengths, and life cycle events. Researchers may use this method to recreate early life stages, including the length of the larval phase and habitat shifts, even for species for which there is a lack of egg or larval data. The first annual ring's timing and the duration of the growth season, for instance, have been

confirmed using daily increment analysis, which also sheds light on how fish react to environmental changes like temperature swings(Ding et al., 2020; Spich & Fey, 2022; Sponaugle, 2010). Otoliths also use changes in their microstructure and chemical makeup to document physiological and environmental events, such as dietary or habitat changes. Otoliths can be microchemically analyzed to reconstruct environmental histories and identify anthropogenic impacts; whole-otolith and surface examinations provide complementing benefits. However, certain species might be difficult to interpret from otolith increments, therefore it's important to confirm age estimations and development trends(Spich & Fey, 2022; Sponaugle, 2010). . Otolith microstructure analysis, which offers high-resolution historical records of fish life histories, is an effective tool for fisheries research, ecology, and management overall(Ding et al., 2020; Spich & Fey, 2022; Sponaugle, 2010).

Primary increments in calcified structures like fish otoliths or mollusk shells generally offer high temporal resolution, often reflecting daily growth. However, this periodicity can vary among species and may be difficult to detect in some cases. Under high magnification and transmitted natural light, these increments appear as alternating light mineral-rich ("L zones") and dark organic-rich ("D zones") bands, with thicknesses ranging from less than 1 µm to 12 µm. Dark zones are typically thinner than light ones. Accurate detection and dating of these increments are vital for reconstructing environmental histories and biological processes, as small identification errors can lead to significant misinterpretation of both short-term events and long-term trends. Crossdating, a technique adapted from dendrochronology, is essential to ensure each increment is correctly assigned to its calendar date. Without such rigorous controls, cumulative errors may compromise the reliability of environmental reconstructions(Black et al., 2016)

The second level of temporal resolution in calcified structures involves seasonal zones, visible under transmitted light as alternating dark opaque and bright translucent bands. These zones differ in optical appearance, increment width, organic content, calcium carbonate-to-protein ratio, and trace element composition. Opaque zones usually indicate periods of faster growth, while translucent zones correspond to slower growth, influenced by environmental factors like food availability and seasonal changes. These features typically form on an annual or seasonal cycle, making them useful for reconstructing past environmental conditions and understanding organismal growth rhythms(Pearse & Pearse, 1975).

Annual increments in otoliths are generally visible without high magnification and can reach

widths of about 100 µm, providing reliable indicators of yearly growth. However, stress events may cause structural discontinuities called checks, which can be mistaken for true annual marks. Experimental studies show that physiological stress disrupts daily increment formation, leading to the appearance of these checks, which reflect episodes of stress in the fish's life(Campana, 1983).

- ❖ Otolith microstructure analysis in glass eels (civelles):

The glass eel otolith microstructure provides important information on their migration, metamorphosis, and early life history. Researchers can accurately measure the age of glass eels thanks to otoliths, which are tiny structures in the inner ear of eels that grow by depositing daily increments(Cieri & McCleave, 2001; Lecomte-Finiger, 1992). Significant life events, like hatching and the change from larva (leptocephalus) to glass eel, are indicated by noticeable alterations in the otolith's structure, such as sudden increases in increment width and sharp decreases in strontium-to-calcium (Sr:Ca) ratios. These increments can be seen as rings(Arai et al., 1997; Arai, Otake, et al., 2000).

Usually, the otolith is separated into three parts: the diffuse or metamorphosis zone, which concludes with a transition ring, the growth zone with countable daily increments, and the nucleus (primordium)(Arai, Otake, et al., 2000; Lecomte-Finiger, 1992). These increments are dependable for analyzing age and growth since studies have confirmed that they are deposited daily in both laboratory and outdoor settings(Arai, Limbong, et al., 2000; Cieri & McCleave, 2001). One important element in identifying the site of recruitment and preserving the species distinction between American and European eels is the timing of metamorphosis, as shown by otolith microstructure(Arai, Otake, et al., 2000; Kuroki et al., 2008). Species and geographical differences in the length of the leptocephalus stage and age at recruitment have been noted, indicating adaptations to their migratory paths and spawning grounds(Arai, Otake, et al., 2000; Kuroki et al., 2008; Lecomte-Finiger, 1992).

- ❖ Techniques used to prepare otoliths for age and growth analysis:

Otoliths are prepared for age and growth analysis using a variety of methods, each with unique benefits and drawbacks. In certain species, such as boarfish and bluegill, whole otolith techniques offer age estimates that are equivalent to sectioned otoliths, especially for younger

fish. They are also frequently easier and less expensive(Koch et al., 2019; Silva et al., 2024).

The accuracy of age estimation in the European eel has significantly increased due to advancements in otolith preparation and reading procedures, which have moved from basic to more complex approaches. The first method used in the past was to read whole, cleansed otoliths, but this frequently underestimated age, particularly in older, slower-growing eels(Durif et al. 2020, 200; Vøllestad et Næsje 1988).

Although the "burn-and-crack" method, which involves heating and breaking otoliths to reveal growth rings, represented an early advancement and yielded improved results, its accuracy remained limited, as it correctly estimated age in only about 25% of cases (Vøllestad & Næsje, 1988).

Thin sectioning, which entails polishing and grinding otoliths to obtain thin slices, later became the standard as research progressed. This technique allowed for clearer visualization of annual increments and produced significantly higher and more accurate age estimations, often revealing ages decades older than previously thought(Andrews et al., 2025; Durif et al., 2020). Modern protocols now often include embedding otoliths in resin before sectioning, and may use staining to enhance ring visibility(Andrews et al., 2025) Recent innovations also incorporate chemical and isotopic analyses, such as bomb radiocarbon dating and microchemistry (e.g., Sr:Ca and Ba:Ca ratios), to validate age readings and reconstruct life histories(Andrews et al., 2025; Fablet et al., 2007; Tabouret et al., 2010; Teichert et al., 2022, 2023) These advances have shown that European eels can live much longer than previously estimated, with some individuals reaching up to 70–100 years(Andrews et al., 2025)

PART 2: MATERIALS AND METHODS

The second part provides a brief overview of the study site and the information needed to understand the material and methods used to complete this thesis.

The formulas used to calculate growth indices, determine diet, age, and parasitic epidemiology, as well as perform statistical analysis, will be illustrated later.

1. Study site

2. Eel treatment

- **Structure of the subpopulation studied.**
- **Body growth of the subpopulation studied.**
- **Diet.**
- **Otolithometry.**
- **Parasitism**

3. Statistical analysis

Study areas:

Sampling was conducted seasonally between December 2021 and September 2022 from two localities, Lake Tonga in Wilaya of El Tarf (36°51.511″ N; 8°30.100″ E) and Wadi El Kebir in Wilaya of Jijel (N 36° 32′ 16; E 6° 15′ 54) (Fig. 16, 17).

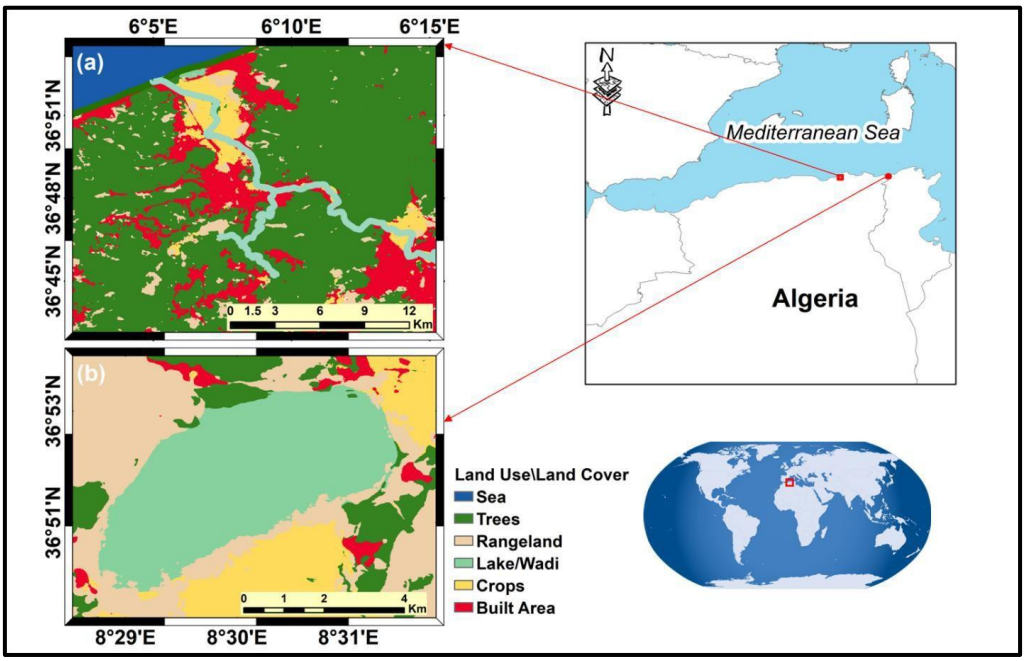

Figure 16: Study area (a) El Kebir wadi (b) Tonga Lake.

Figure 17: Collecting samples during the study (Boughaba, 2021)

1. Lake Tonga:

Lake Tonga, located within the El Kala National Park in northeastern of Algeria, is a large, shallow freshwater ecosystem of approximately 2,200 hectares. Recognized as a Ramsar site of international importance since 1983, the lake has a maximum depth of around 1.5 meters and is primarily fed by two tributaries. It maintains a hydrological connection to the Mediterranean Sea through an artificial canal.

The lake's waters are mildly alkaline (pH 6.5–8.5) and exhibit clear signs of eutrophication, characterized by elevated concentrations of nutrients such as phosphates and ammonium. High levels of fecal bacteria further suggest declining water quality and potential public health concerns. Physicochemical analyses indicate moderate turbidity, low dissolved oxygen levels, and elevated concentrations of chloride and potassium.

Ecologically, Lake Tonga sustains a diverse assemblage of macroinvertebrates and planktonic organisms. These biological communities display marked seasonal and spatial fluctuations, largely influenced by environmental conditions and variations in water quality.

Despite its ecological significance, the lake is subject to increasing anthropogenic pressures, including nutrient loading, organic pollution, and contamination by trace metals, likely originating from adjacent industrial and mining operations. These stressors underscore the critical need for integrated management strategies aimed at mitigating pollution and

safeguarding the lake's biodiversity and ecological function (Loucif et al., 2020; Mahmoudi et al., 2024; Loucif).

1.1. Geology and hydrobiology

Part of a significant wetland system known for its biological value, Lake Tonga is situated in the El Kala National Park in northeastern Algeria, in a low-lying coastal basin. Sedimentary deposits define the region's geology, and it has been discovered that the lake's sediments contain high concentrations of trace metals including iron, lead, and cadmium. Both natural geological background and man-made sources, such as an abandoned mine and steelworks in the nearby watershed, are connected to these toxins. Lead and cadmium are more prevalent close to the lake's outflow, suggesting groundwater discharge from mine leachates, whereas iron pollution is ubiquitous across the lake, most likely as a result of atmospheric deposition from industrial emissions and influx from tributaries (Bourhane-Eddine et al., 2013). In terms of hydrology, Lake Tonga is a shallow, seasonal freshwater lake with a maximum depth of around 1.5 meters. It receives nutrition from two major rivers and is joined to the Mediterranean Sea by an artificial canal, which affects its salinity and water exchange. Variable nutrient inputs (ammonium, nitrates, and nitrites) and dissolved oxygen define the lake's water quality, and pollution levels vary by zone and season. Pollution levels become high and can reach or even exceed the limits set by the World Health Organization.. Because of these hydrological and geological characteristics as well as human influences, Lake Tonga is a dynamic yet delicate environment that has to be managed carefully to maintain its ecological integrity (Bourhane-Eddine et al., 2013; Farida et al., 2015).

1.2. Climate

Lake Tonga experiences a Mediterranean climate, characterized by mild, wet winters and hot, dry summers. Seasonal temperature changes are the most significant climatic factor influencing the lake, with water temperatures and associated biological activity peaking in summer and declining in winter. Studies show that water temperature is the only physicochemical parameter with significant seasonal variation, while other factors like pH, dissolved oxygen, and nutrient concentrations remain relatively stable throughout the year (Djabourabi et al., 2024). These temperature shifts drive changes in the abundance and diversity of aquatic organisms, with the highest macroinvertebrate diversity and zooplankton populations typically recorded in spring and summer (Djabourabi et al., 2024; Mahmoudi et al., 2024). Cyanobacteria, a type of

phytoplankton, reach their maximum abundance in winter, while dinoflagellates and diatoms peak in autumn and spring respectively, reflecting the influence of seasonal climate on plankton communities (Djabourabi et al., 2024). Overall, Lake Tonga's ecological dynamics are shaped by the region's Mediterranean climate, with temperature serving as the main factor influencing seasonal biological trends (Djabourabi et al., 2024; Mahmoudi et al., 2024).

1.3. Flore

Lake Tonga is distinguished by its remarkable botanical diversity, particularly its rich community of bryophytes. A comprehensive floristic survey conducted within the lake's watershed documented 153 species of mosses, encompassing 107 acrocarpous species—characterized by terminal sporophyte development and 46 pleurocarpous species, which exhibit lateral sporophyte formation. These taxa belong to 29 distinct botanical families. This level of bryophyte diversity is considered exceptional within the region and underscores the ecological importance of the relatively undisturbed forest and wetland habitats surrounding the lake(Boukhatem et al., 2017) . In addition to bryophytes, the lake supports a variety of aquatic plants and phytoplankton, with cyanobacteria being the most abundant group, especially in winter, while dinoflagellates and diatoms peak in autumn and spring, respectively (Djabourabi et al., 2024). The combination of mosses, aquatic plants, and diverse plankton communities makes Lake Tonga a hotspot for plant biodiversity in northeastern Algeria (Boukhatem et al., 2017; Djabourabi et al., 2024)

Lake Tonga's abundant and varied vegetation, especially its vast aquatic plant and bryophyte (moss) groups, is an important ecological factor that can affect the European eel's (*Anguilla anguilla*) habitat and general health. Throughout their watery life phases, eels depend on dense aquatic vegetation for vital refuge, feeding grounds, and nursery sites, which promotes their survival and development. Lake Tonga's abundant mosses and aquatic plants stabilize sediments and cycle nutrients, improving water quality and preserving the favorable circumstances required for eel populations (Bakaria et al., 2018). Invertebrates are crucial eel's food sources, and their variety and abundance can be influenced by the structure and complexity of the lake's vegetation. Eels may be more resilient to environmental stresses and pollutants if they have a rich flora, which might help them cope with problems like parasite diseases and habitat changes(Bakaria et al., 2018). Thus, the remarkable plant biodiversity of Lake Tonga is closely linked to the ecological requirements and well-being of the European eel population found there (Bakaria et al., 2018).

1.4. Fauna

Remarkable fauna in Lake Tonga includes a high diversity of an important site for waterbirds, supporting 61 species from 17 families, including endangered species such as the white-headed duck (*Oxyura leucocephala*) and ferruginous duck (*Aythya nyroca*), highlighting its significance as a Ramsar wetland and a key habitat for both resident and migratory birds Peak abundances of these birds have been seen in the winter, when they use the lake for nesting, wintering, and a stopover during migration (Gherib et al., 2022). The aquatic beetle community is also notable, with 24 species identified and diversity peaking in spring (Mahmoudi et al., 2022). Additionally, the lake supports a variety of zooplankton and fish, contributing to its ecological richness (Djabourabi et al., 2024).

A wide variety of insects, especially aquatic ones that are important to the environment, may be found in Lake Tonga. Remarkably, 30 aquatic macroinvertebrate species from 20 families have been found, with Hemiptera (true bugs), Coleoptera (beetles), and many mosquito species being the major groupings (Djamai et al., 2019; Korba et al., 2016). The aquatic beetle community is especially diverse, with 24 species recorded and peak diversity in spring (Mahmoudi et al., 2022). Mosquito surveys have identified 13 species across 5 genera, including important disease vectors such as *Culex pipiens*, *Aedes vexans*, and *Anopheles labranchiae*, highlighting potential public health concerns (Korba et al., 2016). Additionally, the area around Lake Tonga supports a rich assemblage of ground beetles (Carabidae), with 83 species documented, including several new records for Algeria and North Africa (Iboud et al., 2023).

1.5. Importance

Lake Tonga in northern Algeria is ecologically vital as a Ramsar-listed wetland, supporting rich biodiversity and serving as a critical habitat for numerous waterbird species, including several species that are endangered or protected. The lake's ecosystem provides essential services such as water purification, nutrient cycling, and habitat for fish, macroinvertebrates, and plankton, which are key indicators of ecological health. However, Lake Tonga is currently experiencing eutrophication and water quality degradation due to nutrient pollution and bacterial contamination, threatening its ecological balance and the survival of its wildlife. While not a marine environment, the lake's freshwater resources are crucial for local fisheries and can support aquaculture, contributing to food security and livelihoods for surrounding

communities. Economically, Lake Tonga offers opportunities for sustainable fisheries, aquaculture, and ecotourism, which can generate income and employment if managed responsibly. The lake's ecological health underpins these economic benefits, as a degraded ecosystem would reduce fish stocks, harm tourism potential, and increase water treatment costs. Effective management and conservation of Lake Tonga are therefore essential not only for preserving biodiversity but also for sustaining the economic and social well-being of the region.

2. El Kebir Wadi

El Kebir Wadi, formed by the confluence of Wadi Enndja and Wadi Rhumel, is a major river system in northeastern Algeria that plays a crucial ecological and hydrological role in the region, which covers an area of around 1,110 km². Its flow supports a mosaic of diverse habitats, including lakes and marshes, and is essential for the ecological balance of protected wetlands like the Beni Belaid Nature Reserve, a Ramsar site (Hamache et al., 2021a; Lazizi & Laifa, 2020). The wadi sustains high biodiversity, particularly in its macroinvertebrate and aquatic communities, which are sensitive indicators of water quality and ecosystem health (Hamache et al., 2021a; Mammeri et al., 2024; Saal et al., 2021). The river's upstream and downstream sections show distinct ecological characteristics, with natural habitats dominating in less disturbed areas and increased pollution and habitat degradation near urban and agricultural zones (Hamache et al., 2021a; Lazizi & Laifa, 2020; Saal et al., 2021). Seasonal variations and anthropogenic pressures, such as agricultural runoff, untreated wastewater, and industrial discharges, impact water quality, leading to issues like eutrophication and reduced oxygen levels. Despite these challenges, El Kebir Wadi remains a biodiversity hotspot, supporting both pollution-sensitive and tolerant species, and its wetlands provide critical ecosystem services such as water purification, flood regulation, and habitat for migratory birds (Hamache et al., 2021a; Mammeri et al., 2024; Saal et al., 2021). The river's health is vital for the sustainability of the coastal and wetland ecosystems it nourishes, highlighting the need for ongoing conservation and improved water management to protect its ecological and economic value.

2.1. Physical characteristics

El Kebir Wadi is a 60 km river in northeastern Algeria, formed by the confluence of Wadi Enndja and Wadi Rhumel, and it drains a watershed of about 1,110 km² before flowing into the Mediterranean Sea. Its physical characteristics include significant seasonal variation in water temperature (ranging from 11.5°C in wet periods to 23.5°C in dry periods), pH and electrical conductivity, with higher mineralization and pollution levels observed downstream, especially during dry seasons due to reduced flow and increased concentration of pollutants (Lazizi & Laifa, 2020). Sediment analysis reveals a decrease in grain size from upstream (coarse, angular grains) to downstream (finer, more rounded grains), reflecting the influence of fluvial, marine, and aeolian processes (Kermani & Boutiba, 2023). The river's water quality is affected by both natural factors (such as rainfall and substrate) and anthropogenic pressures, including agricultural runoff and urban wastewater, leading to moderate to poor water quality in many sections (Lazizi & Laifa, 2020; Saal et al., 2020). The pH of the wadi remains generally basic throughout the year, ranging from a minimum of 7.37 during the wet season to a maximum of 8.85 in the dry season, with limited seasonal variation. Dissolved oxygen (DO) concentrations display distinct seasonal trends: levels are elevated during the wet season due to increased flow and aeration, reaching up to 11.5 mg/L, while significantly lower concentrations, as low as 1.8 mg/L, are observed in more polluted downstream sections during the dry season. Although the mean DO value is not explicitly stated, the observed range suggests substantial seasonal fluctuation, with improved oxygenation in wetter months and potential hypoxic conditions during drier periods (Lazizi & Laifa, 2020).

2.2. Climate

The climate of the El Kebir Wadi region is typically Mediterranean, marked by mild, wet winters and hot, dry summers. Rainfall generally begins in October and continues until late April, leading to increased river discharge and more connected aquatic habitats during this period. In contrast, the dry season results in significantly reduced water levels, occasionally causing the river to fragment into isolated pools (Hamache et al., 2021b). Seasonal air temperature and precipitation patterns strongly influence the river's hydrology and water quality, with higher temperatures and lower rainfall in summer contributing to increased evaporation and concentration of pollutants.

2.3. Hydrological value

El Kebir Wadi plays a crucial hydrological role in its region by acting as a primary conduit for rainfall runoff, especially during the wet season, and by shaping both water availability and flood risk for surrounding communities. Hydrological modeling shows that the wadi's flow is dominated by rapid surface runoff in response to rainfall events, with minimal contribution from groundwater, making it highly sensitive to seasonal precipitation and intense storms (Maref et al., 2023). This responsiveness means the wadi is central to flood dynamics, as it can quickly channel large volumes of water, posing risks to urban areas and agricultural lands downstream (Djedaiet & Ghachi, 2023). Additionally, El Kebir Wadi transports sediments and nutrients, which play a key role in shaping soil fertility and maintaining the ecological health of adjacent wetlands and coastal zones.

2.4. Flora and fauna

The aquatic flora and fauna of Jijel's El Kebir Wadi are rich and varied, especially its macroinvertebrate populations, which act as markers of ecosystem health and water quality (Mammeri et al., 2024; Saal et al., 2021). With 129 taxa from 77 families and 15 orders, studies have shown a great variety of benthic macroinvertebrates, including several species that are vulnerable to pollution, such as those belonging to the Ephemeroptera, Plecoptera, and Trichoptera groups. The presence of these sensitive taxa suggests that, compared to other regional wadis, El Kebir Wadi supports relatively healthy and less disturbed habitats (Mammeri et al., 2024). Additionally, the wadi hosts a variety of Chironomidae (non-biting midges), which are ecologically important and reflect both natural and anthropogenic influences on the ecosystem (Hamache et al., 2021b). The diversity and distribution of these organisms are shaped by environmental factors such as altitude, water conductivity, dissolved oxygen, and nutrient levels.

Eel treatment and body growth

Sampling was conducted seasonally between December 2021 and September 2022 from two localities Tonga Lake and El Kebir Wadi.

Season	Sampling dates	Lake Tonga (n)	Wadi El-Kébir (n)
Winter	December 2021 – February 2022	30	32
Spring	March – May 2022	31	30
Summer	June – August 2022	30	00
Autumn	September – November 2022	30	30
Total		121	**92**

A total of 213 eels were examined. Eels were captured using fyke nets with a mesh size of 10 mm. To minimize handling stress, the specimens were transported alive to the laboratory in ice-cooled containers. In the laboratory, total length (TL) was measured to the nearest millimeter, and total weight (TW) was recorded to the nearest gram using a precision balance (fig. 18).

Figure 18: Biometric measurements of captured eels (left: length measurement; right: weight recording) (Boughaba, 2021).

1. The Pectoral Fin Index (PFI%):

Pectoral fin length (Lp) was measured to the nearest millimeter (Fig. 19) and standardized by the total length (TL) of the individual to calculate the pectoral fin index (PFI, expressed as a percentage), using the following formula:

PFI%= (Lp/Lt) × 100

Durif (2003) reported an increase in PFI from the yellow stage (PFI < 4%) to the silver stage (PFI ≥ 5%). Therefore, the PFI serves as an indicator of the eel's physiological progress toward transoceanic migration.

Figure 19: Measure the pectoral fin of the captured eel (Boughaba, 2021).

2. The Eye Index (EI):

The horizontal and vertical diameters of both left and right eyes (DhL, DhR, DvL, DvR) were measured to the nearest tenth of a millimeter (Fig. 20). Defined by Pankhurst (1982) as the ratio between the total length of the eel and the average size of its two eyes, the eye index (EI) was calculated using the following formula:

$$EI = \{[(DvL + DhL)/4 \times (DvR + DhR)/4 \times \pi] / TL\} \times 100$$

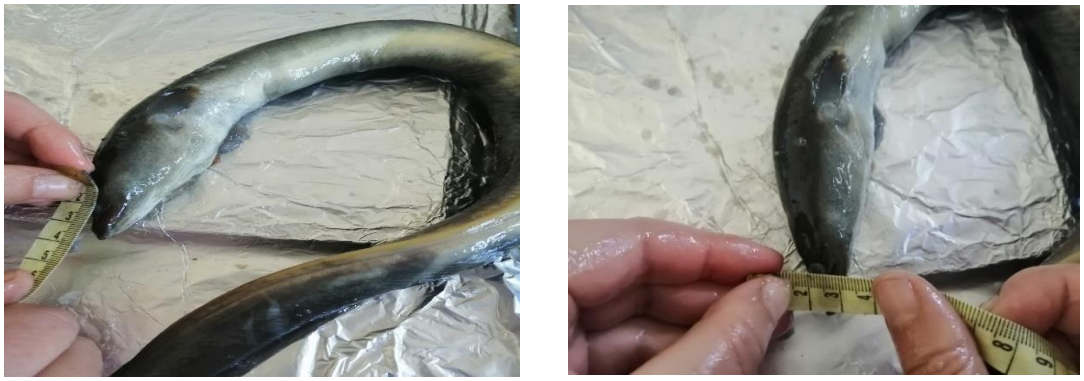

Figure 20: Measurement of eye diameters (left: horizontal diameter; right: vertical diameter) (Boughaba, 2021).

3. Determination of Sexual Maturity Stage:

The sexual maturity stage (S) is determined based on the morphometric data of each individual: total length (in mm), total weight (in g), pectoral fin length (in mm), and eye diameter (in mm), as previously measured.

For each maturity stage (i), the index **S** is calculated using the following formula:

$$Si = K + L \cdot Li + P \cdot Pi + D \cdot Di + Lp \cdot Lpi$$

where **Li**, **Pi**, **Di**, and **Lpi** are the weighting coefficients presented in Table 4. Only the maximum **S** value is ultimately retained to determine the eel's maturity stage.

Table 4: Weighting coefficients used for the determination of sexual maturity stages in European eels (*Anguilla anguilla*), as defined by Durif et al. (2005)

Migration phase	Resident	Resident	Pre-migrant	Migrant	Migrant	Migrant
Sexual maturity stage	I (undifferentiated)	FII (female)	FIII (female)	FIV (female)	FV (female)	MII (male)
Constant K	-61.276	-87.995	-109.014	-113.556	-128.204	-84.672
Body length (Li)	0.242	0.286	0.28	0.218	0.242	0.176
Weight (Pi)	-0.108	-0.125	-0.127	-0.103	-0.136	-0.116
Mean eye diameter (Di)	5.546	6.6627	9.108	12.187	12.504	12.218
Pectoral fin length (Lpi)	0.614	0.838	1.182	1.23	1.821	1.295

4. Size Class Distribution According to the GRISAM Framework (Briand et al., 2006b)

Size classes (Table 5) were established by the "Eel" working group of the GIS on Diadromous Fish (GRISAM) as part of the development of the European eel (*Anguilla anguilla*) management plan for French river basins.

Table 5: Size classes and corresponding life stages for the European eel, as defined by GRISAM (Briand et al., 2006)

Size (mm)	Description
50–150 mm	Individual in their 1st or 2nd year of continental life
150–300 mm	Growing individual (2 to 6 continental summers of growth depending on sites and individuals)
300–450 mm	Male individual possibly silvering or female individual growing
450–600 mm	Female individual possibly silvering. Small sizes (150–400 g), most often associated with shallow environments
600–750 mm	Female individual possibly silvering. Medium sizes (400–800 g)
> 750 mm	Female individual possibly silvering. Large sizes (> 800 g), most often associated with deep environments

5. Body Growth of the Studied Subpopulation

- *Length–Weight Relationship*

The relationship between total length (TL) and total weight (TW) is expressed by the following equation (Ricker, 1973):

$$Tw = a \cdot TL^b$$

Where:

- **a**: constant
- **b**: allometric coefficient

The allometric coefficient (**b**) reflects the body shape of the fish and generally varies between 2 and 4. When **b = 3**, growth is described as *isometric*; according to Folkvord and Mosegaard (2002), it implies that the growth rate is identical for all body parts. Conversely, when **b ≠ 3**, growth is *allometric*—negative allometry if **b < 3** and positive allometry if **b > 3**—indicating differences between weight and length growth rates.

- *Condition Factor (K):*

The condition factor provides a rapid assessment of the physiological state of individuals and offers a relative measure of the energetic potential of the studied eels. It is calculated as:

$$K = 10^6 . Tw/TL^3$$

- *Growth Modelling*

The most widely used growth model in fisheries science, the von Bertalanffy Growth Function (VBGF) (Panfili *et al.*, 2002), was applied in this study. In its length-based form, the model is expressed as follows:

$$L_t = L_\infty \cdot (1 - e^{-K \cdot (t - t_0)})$$

were:

Lt is the length at time **t**, **L∞** the maximum theoretical length towards which the length of the fish tends, **k** is the rate at which the length approaches L∞, and **to** is the (hypothetical) time at which the fish would have been zero size if it had always grown according to the von Bertalanffy equation.

$$W_t = W_\infty \ (1 - e \quad)^3 \qquad (\quad ^{-K(t - t_0)}$$

6. Internal index

- *Gonadosomatic Index (GSI%):*

Gonad weight (GW) was measured to the nearest gram to calculate the gonadosomatic index (GSI) using the following formula:

$$\text{GSI (\%)} = \text{GW/TW} \times 100$$

Where:

- **GW**: gonad weight (g)

The GSI is used to assess gonadal maturity in silver eels, with threshold values of **GSI > 0.2%** for males and **GSI > 1%** for females at the time of downstream migration (Fontaine, 1994; Marchelidon *et al.*, 1999; Acou *et al.*, 2003; Durif, 2003).

- *Hepatosomatic Index (HSI%):*

Liver weight (LW) was measured to the nearest gram (Fig. 21) to calculate the hepatosomatic

index (HSI) according to the following formula:

HSI (%) = LW/TW ×100

Where:

- **LW**: liver weight (g)

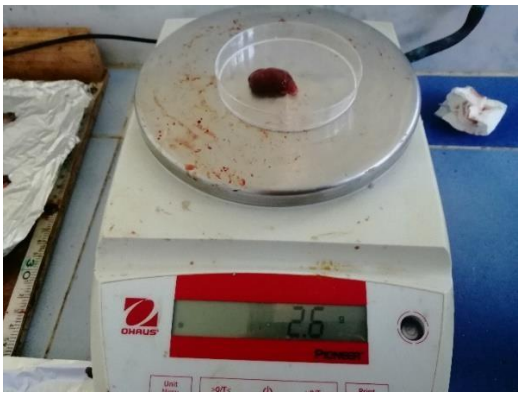

Figure 21: Weighting of the liver (Anguilla anguilla) (Boughaba, 2021).

The HSI of silver eels can vary between 0.5% and 5% depending on sex and individual variability (Durif, 2003). From the yellow to the silver stage, the mean HSI decreases from **1.72 ± 0.59%** to **1.24 ± 0.30%**, as the eel stops feeding prior to its migratory departure.

- *Empty Digestive Tract Somatic Index (EDTSI%):*

The weight of the empty digestive tract (EDTW) was measured to the nearest gram (Fig. 22) to calculate the empty digestive tract somatic index (EDTSI) according to the following formula:

EDTSI (%) =TWED/TW×100

Where:

- **EDTW**: empty digestive tract weight (g)

Figure 22: Weighting of the digestive tract in empty states (Boughaba, 2021).

Diet of *Anguilla Anguilla*

The digestive tracts (Fig.23) were excised by sectioning at the upper level of the esophagus, near the buccal cavity, and at the urogenital papilla (anus). Mesenteric fat was removed when adherent to the intestine. The stomach, pyloric caeca, and intestine were then separated and longitudinally dissected, after which their contents were emptied.

Figure 23: Contents of the gut (Boughaba, 2021).

Using a stereomicroscope, the various ingested prey items were examined, after which several parameters were evaluated to characterize the diet:

1. Vacuity coefficient (CV%)

This parameter quantifies feeding activity. It is calculated as the number of empty digestive tracts (*Nv*) relative to the total number of digestive tracts examined (*N*):

$$CV\% = (Nv/N) \times 100$$

2. Frequency of occurrence (F%)

This parameter represents the percentage of digestive tracts containing a given prey item (Ni) relative to the total number of full digestive tracts examined (Np), and is calculated as:

$$F\% = (Ni/Np) \times 100$$

Otolithometry

1. Extraction

A transverse section of the head was made at the posterior part of the skull, passing through the posterior region of the preopercular bone (Fig. 19). The entire head was then severed, and the anterior part was separated from the rest of the body. The posterior part of the brain (medulla oblongata) thus became visible in the upper portion of the skull, with the two cavities of the inner ears located laterally and beneath the brain. The otoliths were then directly extracted using fine forceps (Panfili et al., 2002).

2. Cleaning and Storage

To remove any remaining macula or vestibular tissues adhering after dissection, the otoliths were mechanically cleaned by gently removing the tissues with fine forceps or by hand. They were then air-dried at room temperature and placed in labelled bags, with left and right otoliths kept separate, for later examination. Finally, the samples were stored in a cool, dark place.

3. Observation

The clarity of the growth marks on the otoliths from captured eels allowed for direct interpretation without prior preparation, using an ‘OPTIKA’ stereomicroscope (Fig. 24) under reflected light against a dark background. The use of a clearing medium (alcohol) was found to be necessary to enhance contrast and improve the visibility of the growth marks.

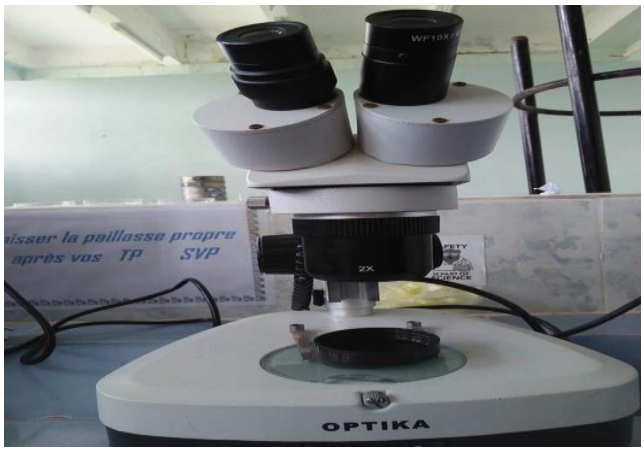

Figure 24:OPTIKA stereomicroscope under reflected light illumination (Boughaba, 2021).

4. Growth Marks on Whole Otoliths:

An alternation of seasonal growth marks is visible on whole otoliths: opaque zones (hyper-calcified areas appearing white under reflected light) alternate with hyaline zones (less densely calcified areas appearing dark). The opaque zone is generally associated with a period of rapid growth (spring–summer), whereas the hyaline zone corresponds to a period of slower growth (winter). Under unfavorable conditions, one or more complete cessations of both linear and weight growth may occur, leading to a marked reduction—or even absence—of otolith deposition. At these points, calcification is very low or absent. The counting of 'Lignes d'Arrêt de Croissance' (L.A.C., or growth cessation lines) is used to estimate the individual age of the fish, with the assumption of one L.A.C. forming each winter. The interpretation of growth marks is based on identifying a consistent pattern within the opaque and hyaline zones, as well as distinguishing annual growth cessations from incidental growth disturbances caused by random life events (e.g., stress, fasting). In the European eel, the annulus generally consists of the association of one opaque zone with one or more hyaline zones, and the annual growth cessation is located at the outer limit of the opaque zone (Panfili et al., 2002).

❖ *Main Structural Zones of Eel Otoliths*

In eel otoliths, two main structural zones can be distinguished:

- The center or nucleus, corresponding to the "glass eel" stage; it is delimited by the transition mark, which indicates the arrival of glass eels in continental waters and their

transformation into elvers. The age of glass eels is generally determined by examining growth micro-increments using scanning electron microscopy.

- The peripheral zone, corresponding to the growth of eels in continental habitats prior to downstream migration and departure from the catchment. Its interpretation is carried out by observing the annuli or growth cessation marks under a stereomicroscope.

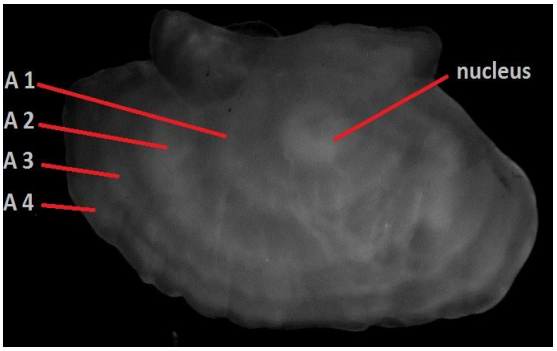

Figure 25: Interpretation of growth marks on the otolith of a European eel (*Anguilla anguilla*) aged 55 months (4+ years) (Tahri, 2015).

5. Age Estimation:

The age of the captured eels was determined by first identifying all visible growth marks on the otoliths and subsequently counting the seasonal rings, assuming an annual formation pattern. To minimize potential sources of bias, each otolith was read on more than three separate occasions. The age in months for each sampled eel was then calculated according to the following procedure:

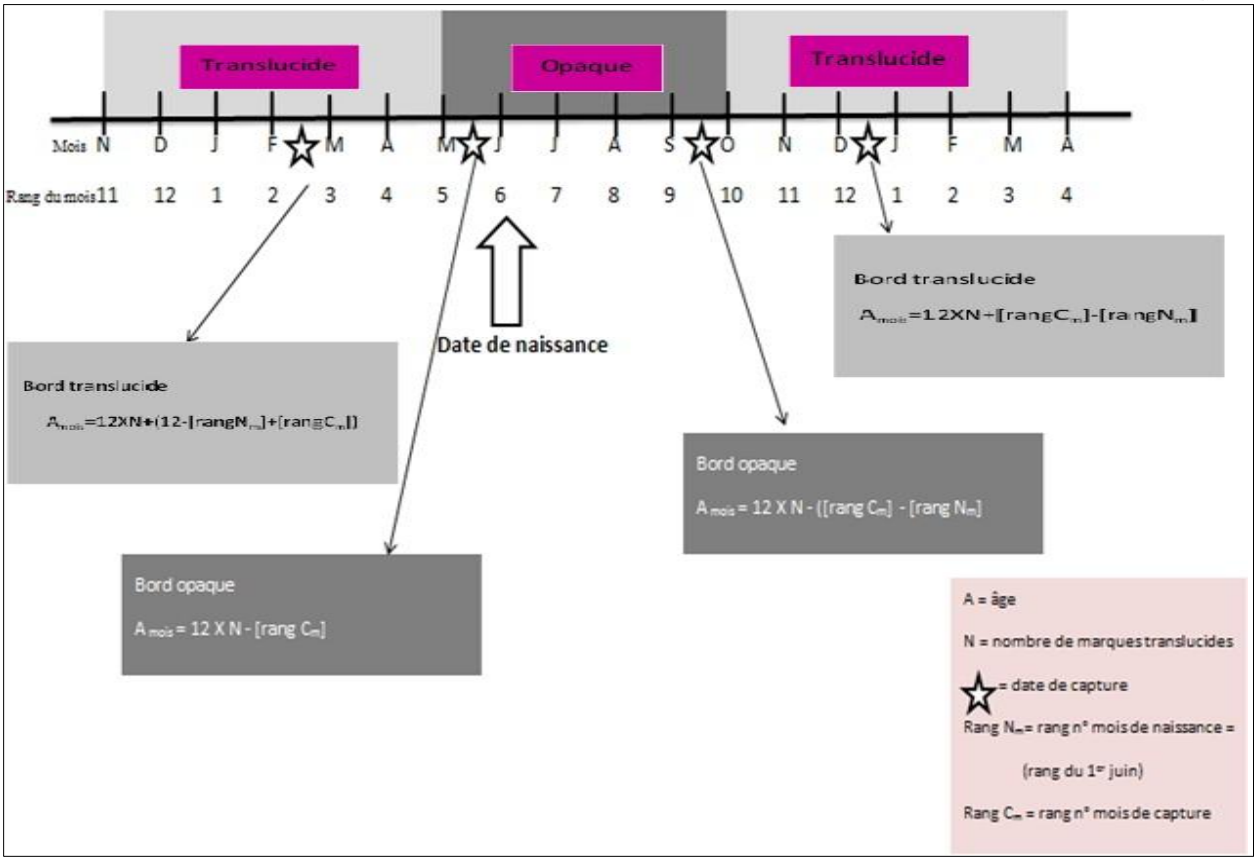

Figure 26: Theoretical method for estimating the age of *Anguilla anguilla* from otolith readings (Panfili et al., 2002).

- *Validation methods*

Validation is an essential step in sclerochronological studies, particularly for species without prior age determination work. Validation methods are generally grouped into three categories: **direct**, **indirect**, and **semi-direct**.

Parasitism

1. Parasites identification

A stereomicroscope (Olympus SZX10) was used to identify the parasites based on their anatomical and morphological characteristics. Instead of using sharp tools that may breach their structures, specimens were handled and moved cautiously using pipettes or delicate brushes to avoid harm (Fig. **27**).

Figure 27: A stereomicroscope (Olympus SZX10) (Boughaba, 2021).

The gills were frozen overnight after removal to aid in the separation of parasites. To effectively release parasites, the gills should be frozen for at least 12 hours before fixation, according to Mizelle (1938). The gill arches to be examined were placed in a 100 mL test tube that was two-thirds full of water. The parasites may be removed from the gill filaments with just a good shake.

Once on a Petri plate, the resultant sediment was diluted until it was clear enough to view under a stereomicroscope. After that, each parasite was extracted using a capillary pipette, washed many times in regular water, and examined under a stereomicroscope (Price & Gery, 1968; Charles & Géry's, 1968).

2. Conservation

Following each treatment, a distinct vial containing 70% ethanol was used to preserve each parasite species from each organ. Along with the parasite's location within the host, each vial was tagged with the date and place of the fish captured.

3. Parasitological Indices

Prevalence, intensity, and abundance are the most often used indicators of parasite population levels in the host (Bush et al., 1997):

$$\textbf{Prevalence}\ (\%)_{\text{total els}} = \frac{N_{\text{infected els}}}{} \times 100$$

$$\textbf{Mean abundance}_{\text{hosts examined}} = \frac{P_{\text{total parasites in all hosts}}}{N}$$

$$\textbf{Mean intensity}_{\text{hosts infected}} = \frac{P_{\text{total parasites in all hosts}}}{N}$$

Where:

- N of infected eels = number of eels infected by at least one parasite
- N of total eels= total number of eels examined
- P total in infected eels= total number of parasites recorded in infected eels

Statistical Analysis

All statistical analyses in this study (growth modelling, correlation, etc…) were performed using the **R software** for data analysis and processing.

To investigate potential relationships between the different growth indices, we applied the Bravais–Pearson linear correlation coefficient. This coefficient, denoted as "*r*," measures the strength of association between two quantitative variables, provided that this relationship is linear or approximately linear.

For two variables *x* and *y*, the correlation coefficient is calculated as follows:

$$r = \frac{\mathrm{Cov}(x, y)}{s_x \cdot s_y}$$

where Cov(x,y) represents the covariance of *x* and *y*, and $\mathbf{s_x}$ and $\mathbf{s_y}$ represent the standard deviations of *x* and *y*, respectively.

The value of *r* ranges between –1 and +1. In absolute terms, the closer *r* is to 1, The more closely the two variables are related, as long as the relationship is linear or roughly linear. A value near zero indicates little to no correlation.

The sign of the coefficient indicates the direction of the relationship (Dagnelie, 1998):

- *A positive correlation* means that higher values of one variable are generally associated with higher values of the other.
- *A negative correlation* indicates that higher values of one variable are generally associated with lower values of the other, and vice versa.

PART 3: RESULTS

In this section, the results obtained during the study are presented and interpreted. The analysis focuses on several key aspects of the studied eel subpopulation, including its structural characteristics, growth patterns, feeding behavior, and age determination through otolithometry. In addition, particular attention is given to the parasitic infestations affecting the captured eels. Together, these elements provide a comprehensive understanding of the biological and ecological status of the studied subpopulation.

1. STRUCTURE OF THE SUBPOPULATION

1.1. Characterization of the captured eel subpopulation

- *Length classes of the captured eels*

The length-frequency distribution of the captured eels revealed a wide range of length classes, from 350 mm to 750 mm total length. The majority of individuals were concentrated in the 400–450 mm and 450–500 mm classes, which represented the modal groups of the subpopulation. These classes accounted for the highest frequencies, particularly in Lake Tonga, where more than 35 individuals were recorded in the 450–500 mm class. In contrast, very few individuals exceeded 650 mm in both sites where the 2 populations exhibited a similar pattern, with dominance of medium- length classes (400–500 mm), though the Lake Tonga generally showed higher abundances across most classes, particularly in the 400–500 mm range (Fig28).

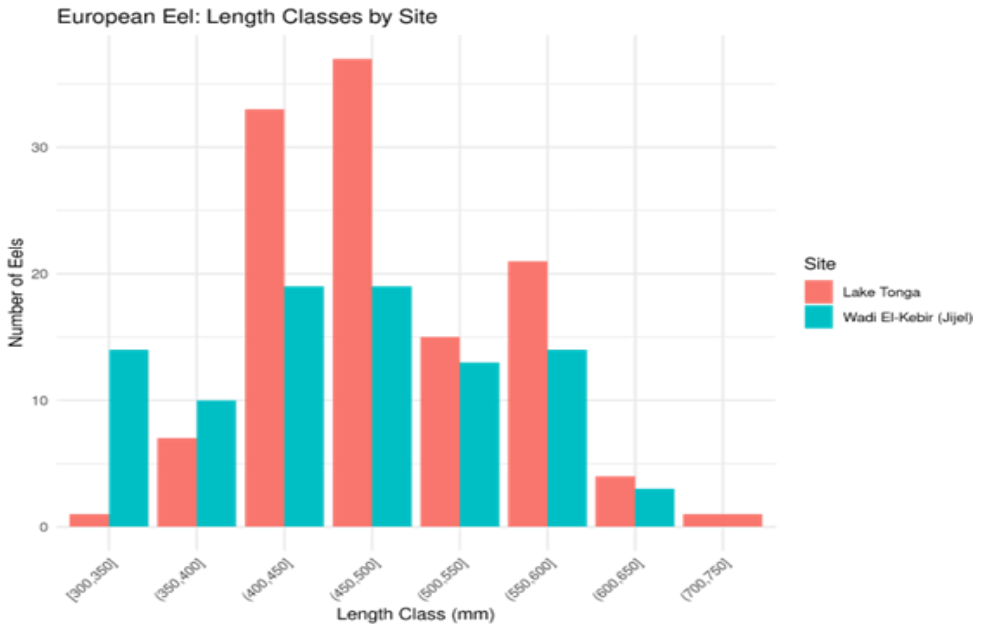

Figure 28: Distribution of length classes of the captured eels.

- *Weight classes of the captured eels:*

The weight of the eels sampled in Lake Tonga and Wadi El-Kebir ranged from 100 g to 900 g and from 100 g to 500 g, respectively, with most individuals falling within the 200–400 g class in both sites (Fig.29).

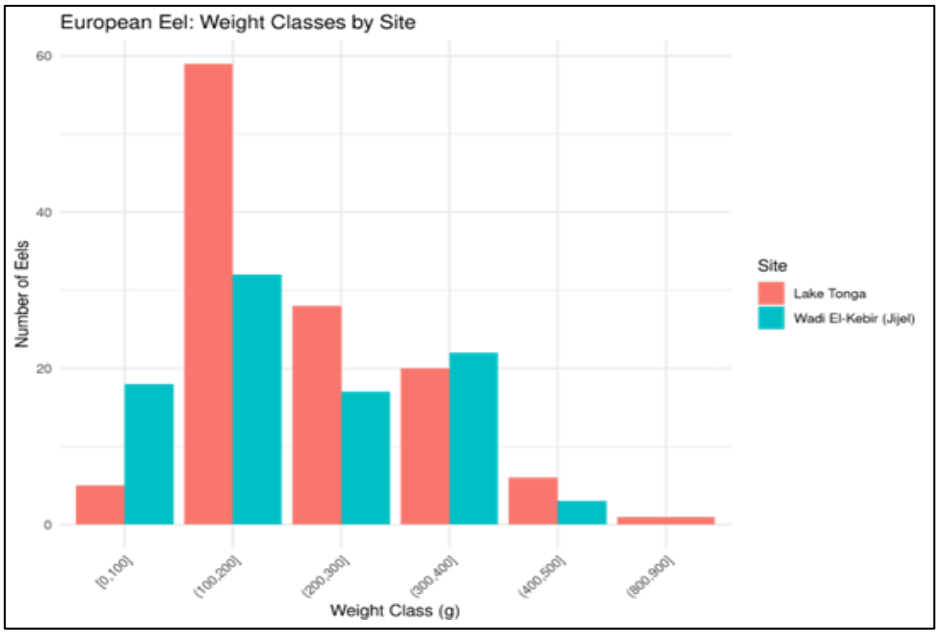

Figure 29: Distribution of weight classes of the captured eels.

- *Seasonal variation in the mean length of the captured eels:*

In Wadi El-Kebir, the lowest mean length was observed in winter, while in spring and autumn it ranged from 400 to 550 mm; concerning the distribution of captured eels in Tonga Lake, there were observed during all seasons (Fig.30).

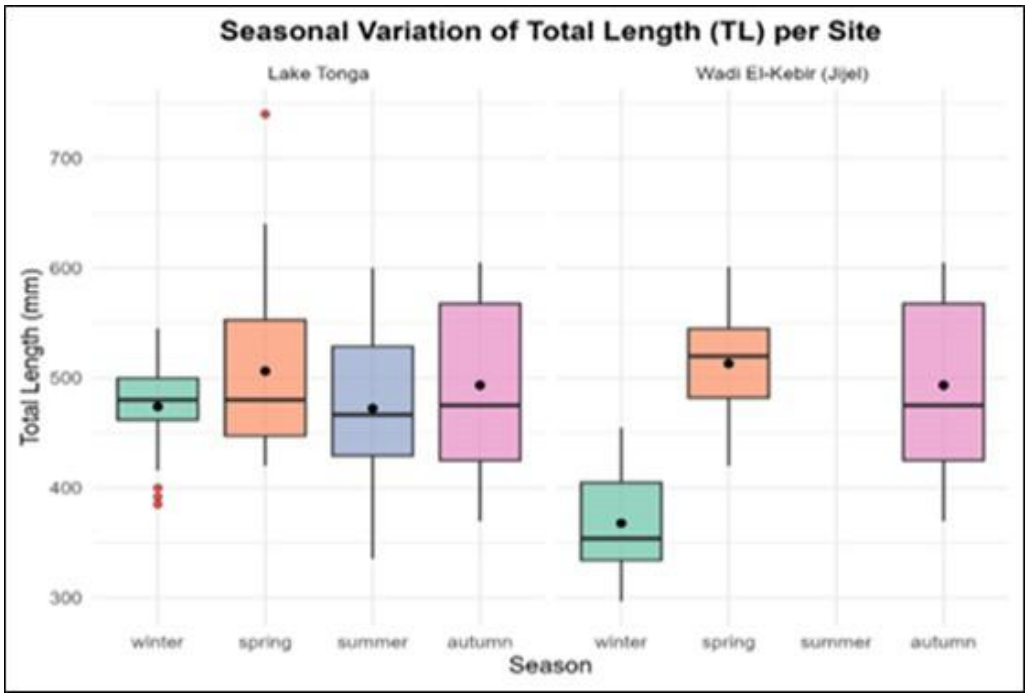

Figure 30: Seasonal variation in the mean length of the captured eels.

- *Seasonal variation in the mean weight of the captured eels:*

In Lake Tonga, eel weights showed clear seasonal variation. The lowest mean weights were observed in winter (≈180 g), whereas the highest values occurred in spring and autumn (≈230–250 g), with some individuals exceeding 800 g in spring. In summer, weights remained intermediate (≈200 g) but with a wide dispersion.

The same distribution pattern was observed in Wadi El-Kebir; indeed, the lowest weights were also recorded in winter (≈120 g), while higher mean values were observed in spring and autumn (≈230–250 g). Summer values were slightly lower but comparable to spring (Fig . 31).

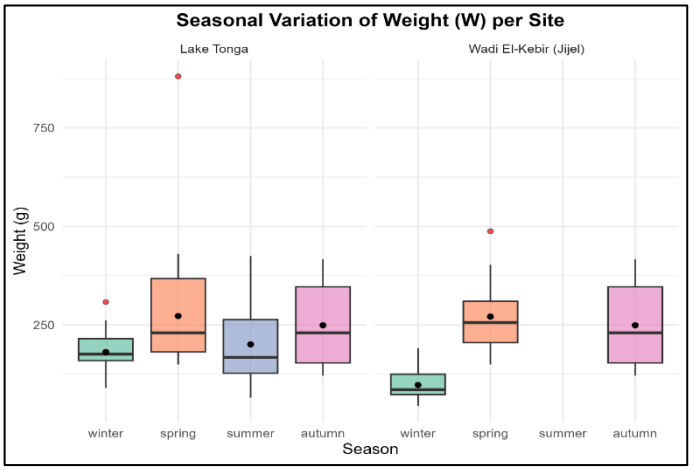

Figure 32: Seasonal variation in the mean weight of the

1.2. Application of four quality indicators for silver eels:

The developmental stages of the sampled eels were assessed using 4 complementary approaches: determination of sexual maturity stage according to **EELREP (2005)**, calculation of the **Ocular Index** (Pankhurst, 1982), estimation of the **Pectoral Fin Index** (Durif et al., 2005), and analysis of length-class distribution following the **GRISAM protocol** (Briand et al., 2

Figure 31: Seasonal variation in the mean weight of the captured eels.

- *Sexual maturity stage according to EELREP (2005):*

In both sites, the eel population was largely dominated by resident individuals followed by migrant eels (Fig.33).

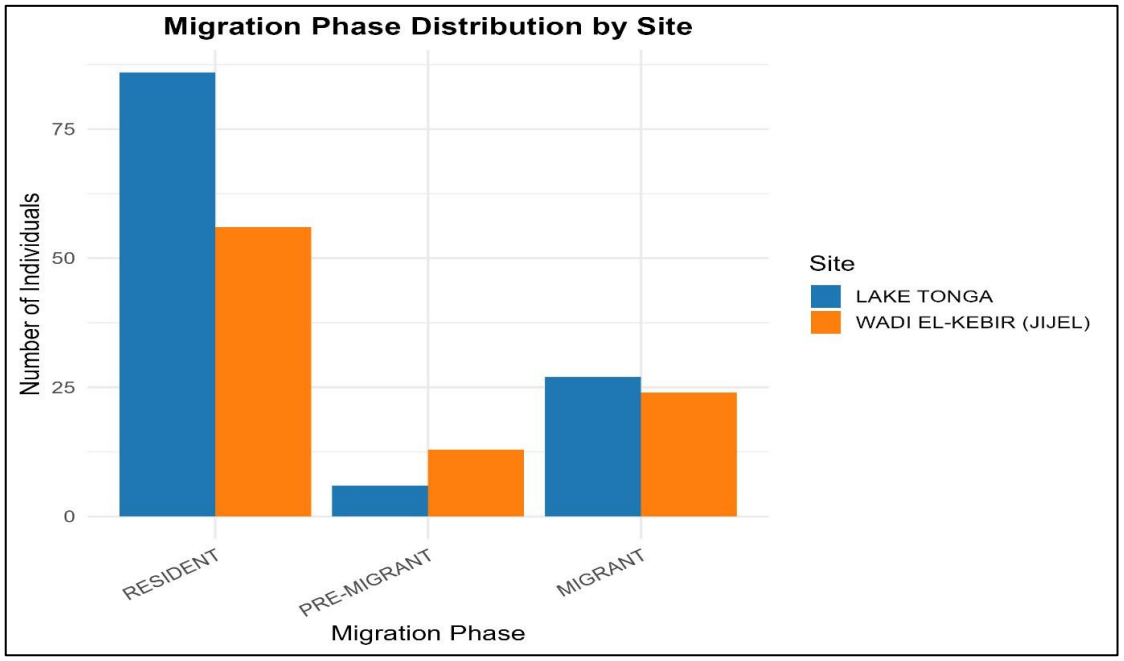

Figure 33: Distribution of the different eel migration stages according to the s-index.

The distribution of sexual maturity stages, according to the EELREP (2005) classification, revealed a predominance of immature (stage I) and early maturing individuals (stage FII) in both sites. Advanced maturing stages (FIII–FIV) and male silver eels (stage MII) were less represented (Fig.34).

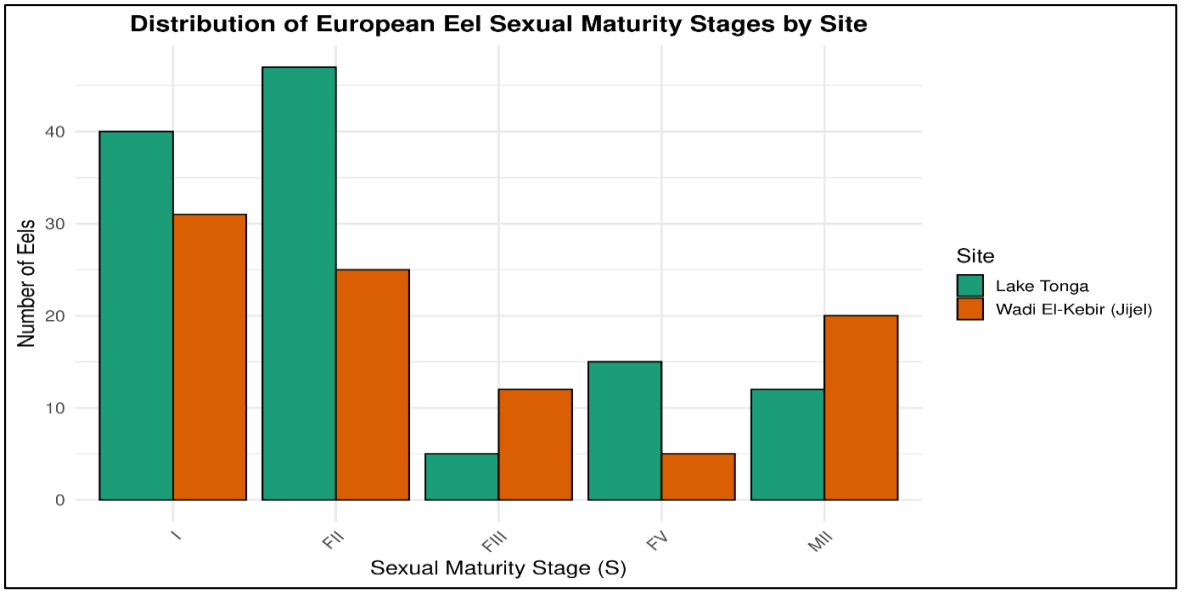

Figure 34: Distribution of eel developmental stages according to the EELREP (2005).

- *Distribution of eels based on the Eye Index (Pankhurst, 1982):*

Based on the Eye Index, most eels from Lake Tonga (85%) were classified as yellow eels, while only 15% reached the silver stage. At Wadi El Kebir, a higher proportion of silver eels was observed (40%), compared to 60% yellow eels (Fig .35).

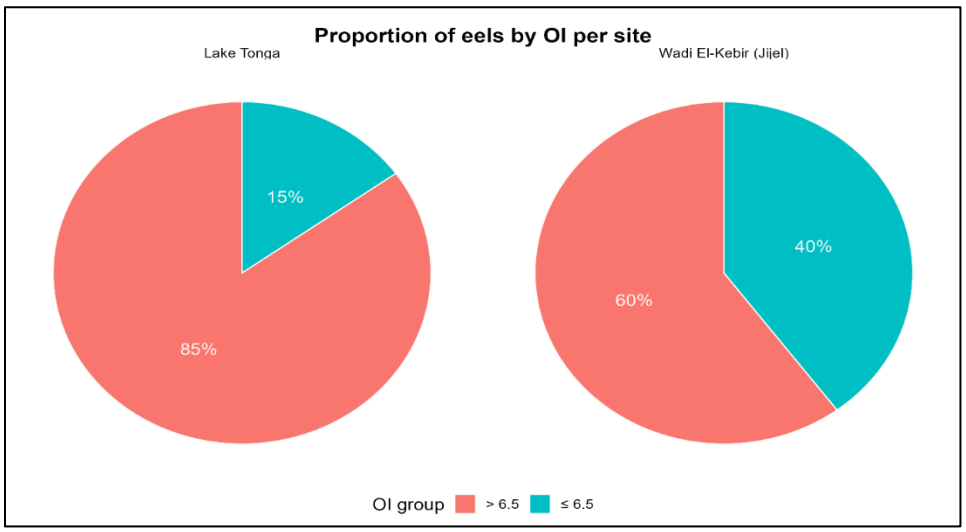

Figure 35: Distribution of eels based on the Eye Index.

- *Seasonal variation in the mean Eye Index of the captured eels:*

Eels from Lake Tonga consistently exhibited higher Eye Index values across all seasons (ranging from ~7.8 to just above 8.0), with a slight increase observed in spring and autumn. In contrast, eels from Wadi El-Kebir showed lower values (ranging from ~6.5 to 7.2), with the lowest mean EI recorded in spring (~6.5), followed by a gradual increase during autumn (~6.8) (Fig. 8).

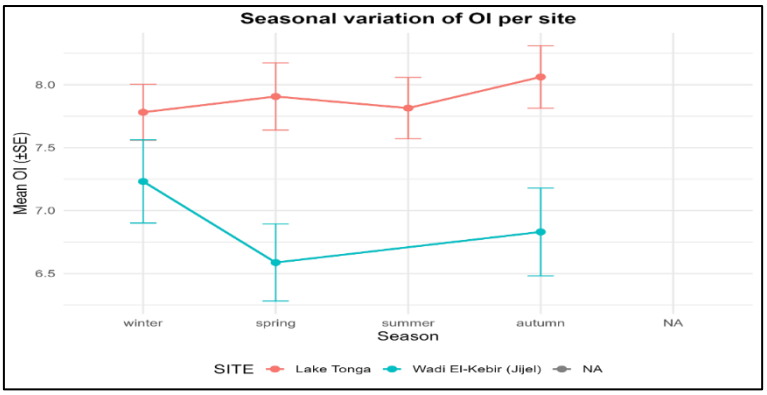

Figure 36: Seasonal variation in the mean Eye Index (EI)

- *proportion of the sampled eels according to the Pectoral Fin Index (PFI):*

Nearly half of the eels captured at both sites were classified as indeterminate according to the Pectoral Fin Index (PFI). A predominance of intermediate-stage eels characterizes eels of both sites, but Wadi El-Kebir exhibits a higher proportion of both silver and yellow eels, while Lake Tonga maintains a slightly more homogeneous distribution centered on intermediate individuals (Fig.37).

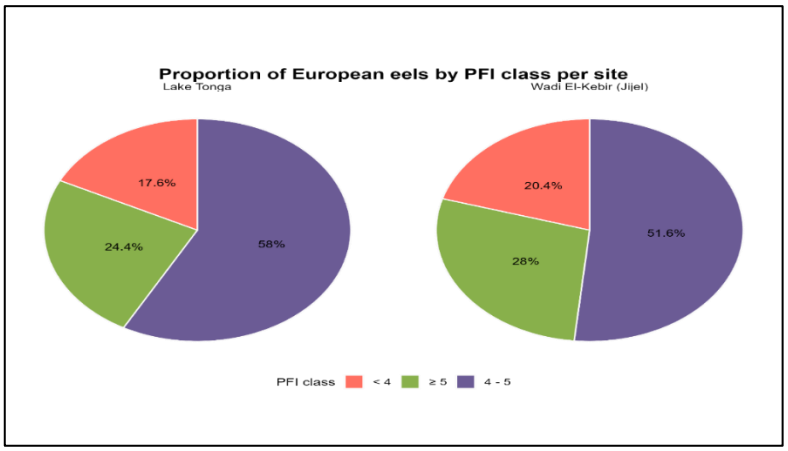

Figure 37: proportion of captured eels by PFI.

Seasonal variation of the PFI of the sampled eels:

Across all seasons, most of eels captured exhibited a mean Pectoral Fin Index (PFI) ranging between 4 and 5 (Fig.38).

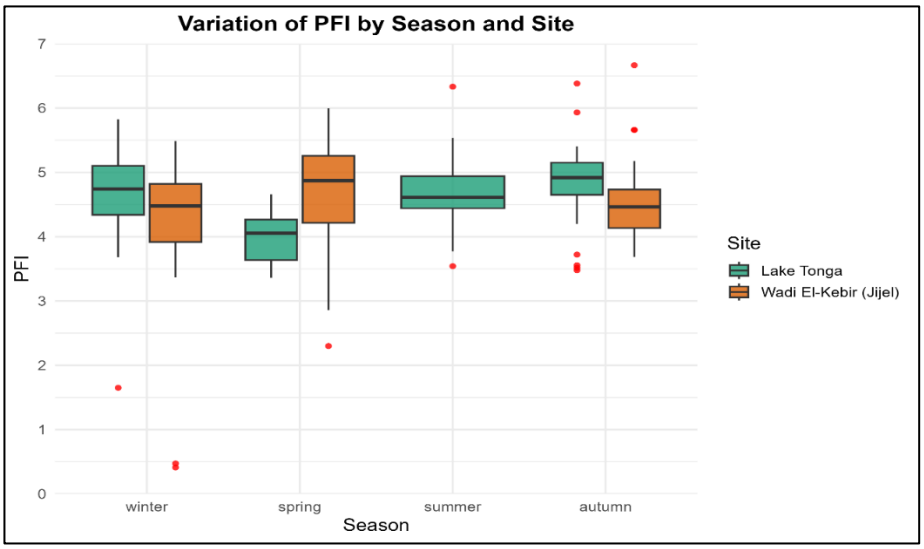

Figure 38: Seasonal variation of the mean PFI.

- *Distribution of Size Classes According to GRISAM*

The captured eels ranged in length from 250 mm to 750 mm. Nevertheless, the distribution of length classes varied between the two sampling sites. Based on the GRISAM classification, the following patterns were observed (Fig.39):

❖ **In Lake Tonga**

- For the 350–450 mm size class (~35 eels), this shows a strong presence of mid-length eels, indicating a juvenile to sub-adult population stage. It suggests successful recruitment and survival at this stage of growth.
- The 450–550 mm class has the highest count (~50 eels), reflecting a dominant mature adult group. This peak indicates favorable habitat conditions in Lake Tonga that support growth and survival towards reproductive maturity.
- Eels in the 550–650 mm class (~30 eels) represent older adults, showing the lake also supports eels approaching larger lengths, possibly reflecting good food availability and habitat quality.
- The very low number of eels in the 650–750 mm class (~1 eel) may suggest that few eels reach the largest length, potentially due to natural mortality, predation, or fishing pressure at these larger lengths.

❖ **In Wadi El-Kebir**

- The 250–350 mm length class has the largest number of eels (~12 eels), which indicates a higher presence of juveniles or younger eels at this site, suggesting recent or ongoing recruitment.
- In the 350–450 mm length class (~25 eels), there is a moderate number of sub-adult eels, indicating continued eel growth and progression beyond the juvenile stage.
- The 450–550 mm length class (~30 eels) represents mature adults, showing a healthy adult population although somewhat less dense than Lake Tonga.
- The 550–650 mm length class (~15 eels) has fewer older adults, possibly indicating either lower growth to larger sizes or some loss at these stages, potentially due to environmental or anthropogenic pressures.

- The 650–750 mm class has no eels observed, which may suggest that very few eels in Wadi El-Kebir reach the largest length, possibly due to harsher conditions, predation, or fishing impacts limiting growth.
- The 250–350 mm length class has the largest number of eels (~12 eels), which indicates a higher presence of juveniles or younger eels at this site, suggesting recent or ongoing recruitment.
- In the 350–450 mm length class (~25 eels), there is a moderate number of sub-adult eels, indicating continued eel growth and progression beyond the juvenile stage.
- The 450–550 mm length class (~30 eels) represents mature adults, showing a healthy adult population although somewhat less dense than Lake Tonga.
- The 550–650 mm length class (~15 eels) has fewer older adults, possibly indicating either lower growth to larger sizes or some loss at these stages, potentially due to environmental or anthropogenic pressures.
- The 650–750 mm class has no eels observed, which may suggest that very few eels in Wadi El-Kebir reach the largest sizes, possibly due to harsher conditions, predation, or fishing impacts limiting growth.

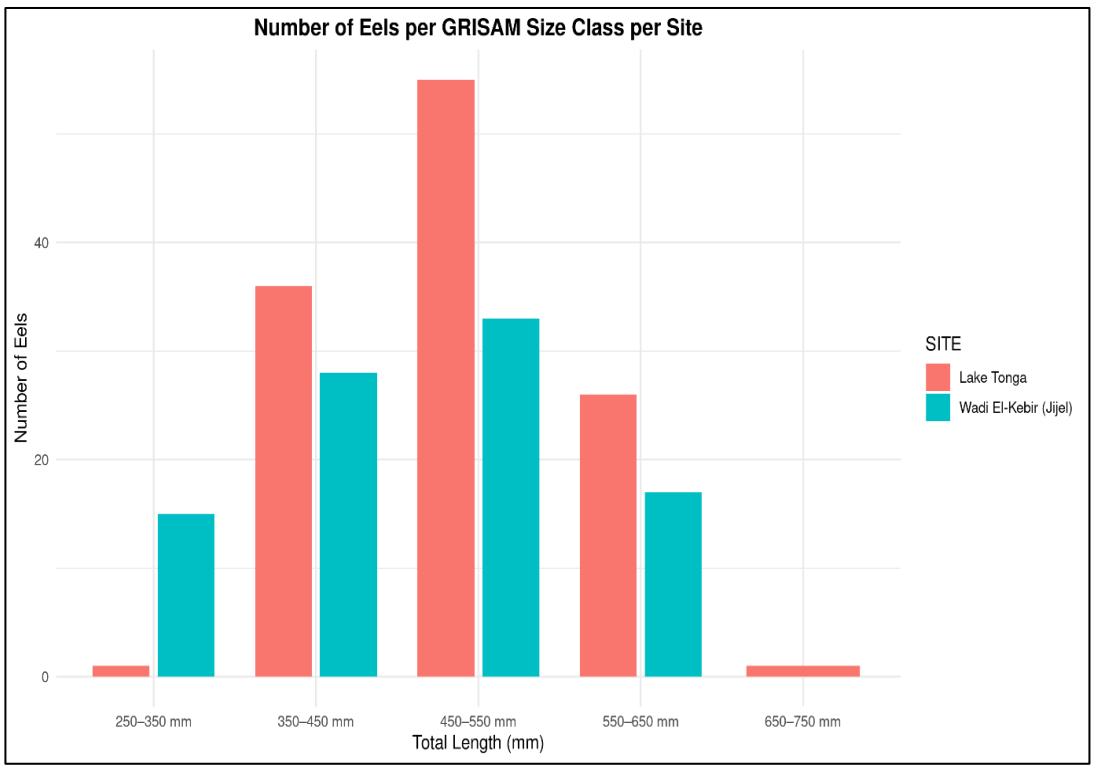

Figure 39: GRISAM classification of captured eels.

2. Somatic growth of the studied subpopulation

2.1. Weight-Length Relationship:

During the sampling campaign, the relative growth, estimated by the equation relating the total length to the total weight of eels caught in Lake Tonga (Fig.12), showed the presence of negative allometry (b = 2.83) with a determination coefficient R^2 of 0.74. This indicates a statistically significant relationship between the evolution of weight and the total length of individuals; in other words, the weight increases at a slower rate than the cube of the total length. This means that as eels grow longer, their weight gain is proportionally less than expected for isometric growth, suggesting they become relatively slenderer.

In contrast, for Wadi El-Kebir (Jijel), the length-weight relationship showed nearly isometric growth with the exponent b=2.95 and R^2=0.95. This suggests that in this site, the weight of the eels increases almost proportionally to the cube of the length, reflecting that the eels maintain their body proportions as they grow (Fig.40).

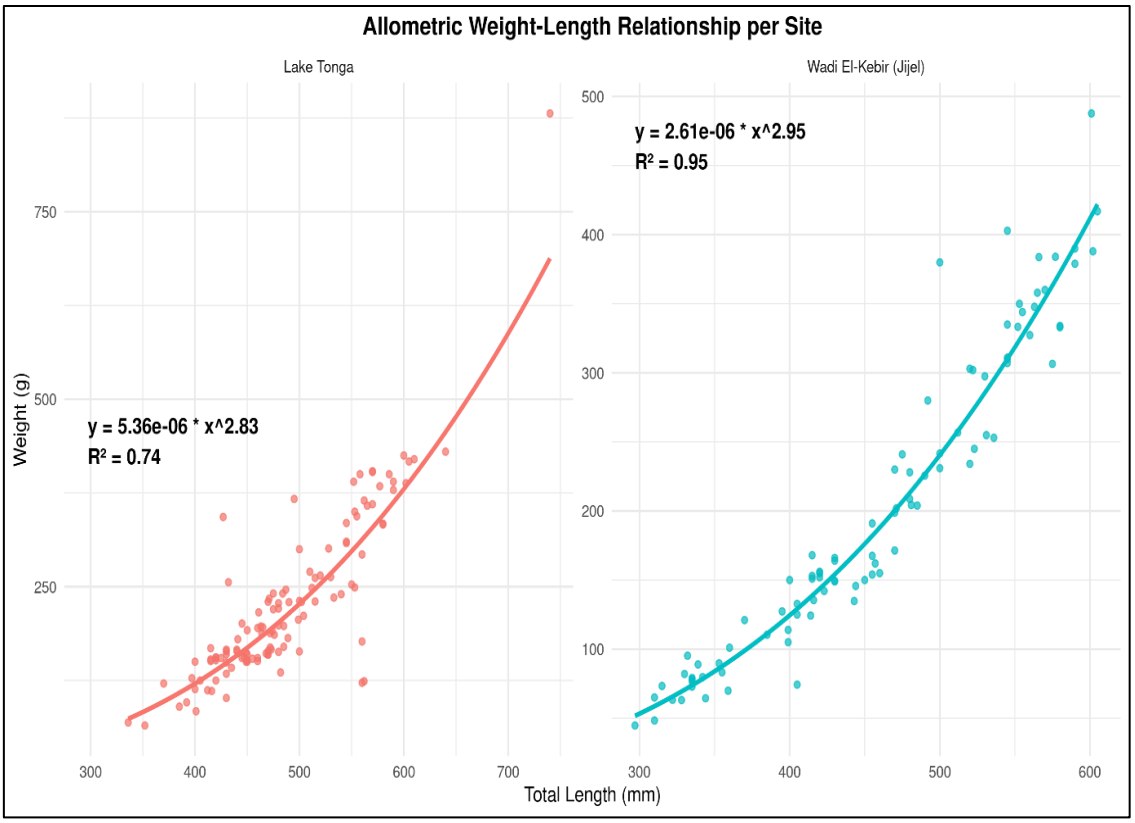

Figure 40: Weight-Length Relationship of eel captured

2.2. Gonadosomatic Index (GSI %):

- *Proportion of GSI in captured eel:*

Females (GSI > 1%) form the majority: about 57.1% of eels in Lake Tonga and 43% in Wadi El-Kebir while males (GSI between 0.2 and 1%) represent 9.2% in Lake Tonga and 23.7% in Wadi El-Kebir. Roughly one third of the captured eels are undifferentiated (GSI ≤ 0.2) (Fig.41).

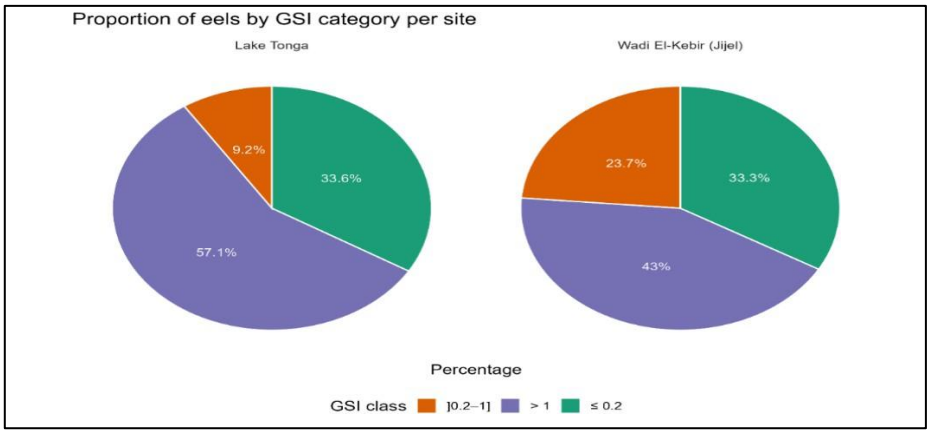

Figure 41: Proportion of the Gonadosomatic Index (GSI %) of captured eels.

- *Seasonal variation of GSI:*

According to the Gonadosomatic Index (GSI %) values, the individuals captured in lake Tonga across all season are considered silver females because their GSI values exceed 1%. Concerning Wadi El-Kebir, GSI is very low (close to 0, with several low outliers) in Winter and shows a peak in spring (median ~1.5, range extending to ~2.0) to return to moderate levels (median ~1.0–1.2) in summer (Fig.42).

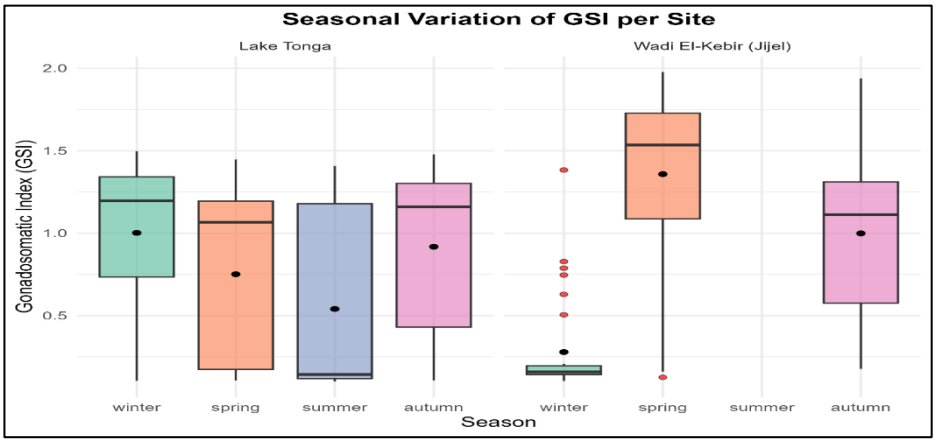

Figure 42: Seasonal variation of the GSI of captured eel.

- *Relationship between the Gonadosomatic Index (GSI) and the length of the captured eels:*

In Lake Tonga, GSI increases significantly with fish length: larger fish tend to have more developed gonads. However, the relatively moderate R^2 (0.41) indicates that length explains only ~41% of the variation in GSI. Concerning Wadi El-Kebir, the relationship is stronger: as fish length increases, GSI rises more steeply compared to Lake Tonga, the higher R^2 (0.70) means 70% of GSI variation is explained by body length, showing a clearer length-dependent reproductive investment (Fig43).

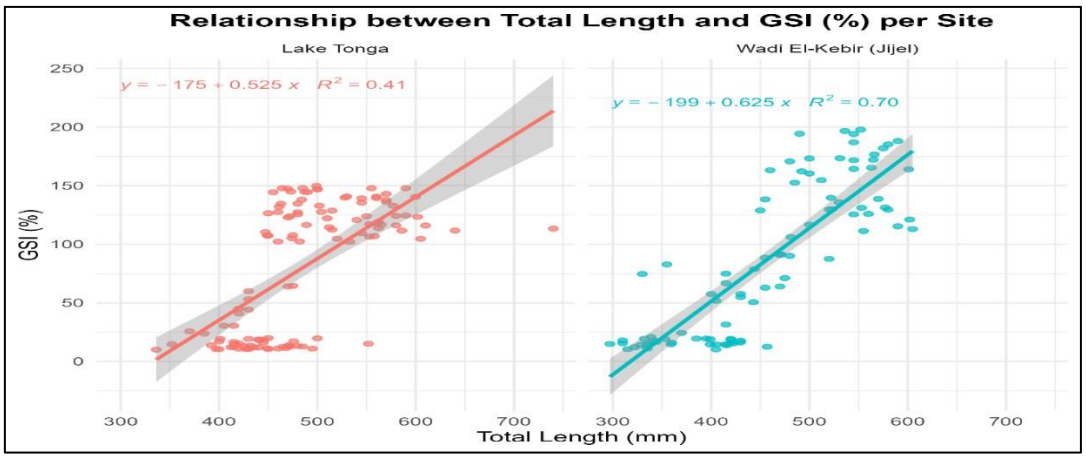

Figure 43: Relationship between GSI (%) and the length of the captured eels.

- *Relationship between the Gonadosomatic Index (GSI) (%) and ocular index OI of captured eels:*

The assessment of the relationship between the GSI and the Ocular Index (OI) of the eels caught in Lake Tonga and El Kebir Wadi revealed positive correlations, with coefficients of determination of $R^2 = 0.33$ and $R^2 = 0.70$, respectively (Fig.44).

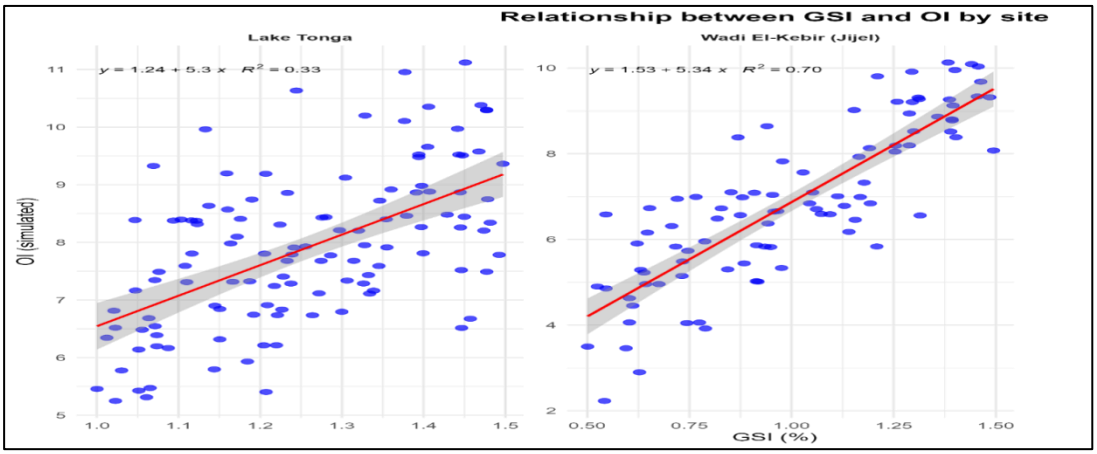

Figure 44:Relationship between (GSI) (%) and ocular index OI of captured eels.

2.3. Hepatosomatic Index (HSI%):

- *Proportion of the Hepatosomatic Index (HSI) of the captured eels:*

In both sites, the hepatosomatic index (HSI) of half of the captured eels was below 1.5, indicating that these individuals can be considered as silver eels (Fig.45).

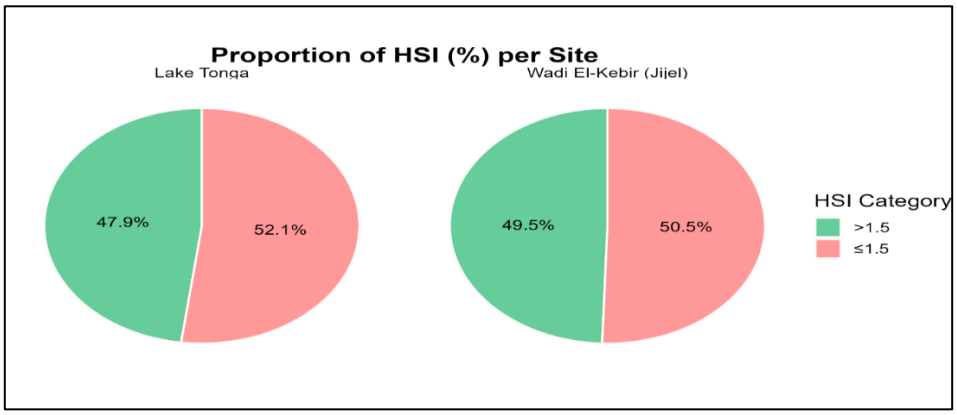

Figure 45: Proportion of (HSI%) of captured eels.

- *Seasonal variation of HSI index:*

At Lake Tonga, the HSI values tend to be lowest in spring (mean ~1.1%) and highest in summer (mean ~1.9%), with outliers present in winter, spring, summer, and autumn. Wadi El-Kebir (Jijel) shows a similar pattern: the lowest HSI in spring (mean ~1.4%), no data points for summer, and moderate HSI values in winter (mean ~1.8%) and autumn (mean ~1.5%). There are some outliers in the spring season for this site as well (Fig.46).

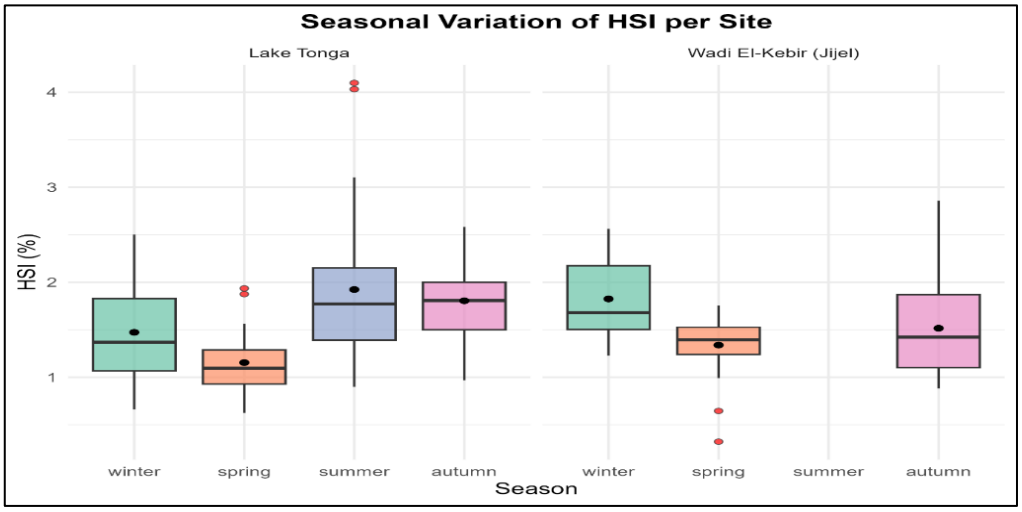

Figure 46: Seasonal variation of HSI index of captured eels.

- *Relationship between the Hepatosomatic Index (HSI) and the weight of the captured eels:*

In both sites, a weak negative correlation was observed between body weight and HSI, indicating that HSI tends to decrease slightly as weight increases. The coefficients of determination were $R^2 = 0.12$ in Lake Tonga and $R^2 = 0.09$ in Wadi El Kebir, both reflecting weak fits (Fig.47).

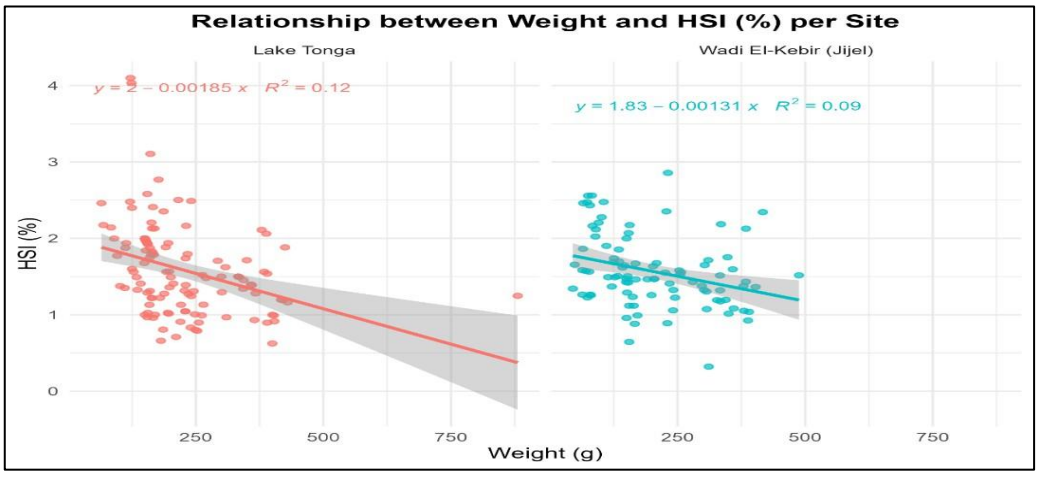

Figure 47: Relationship between the Hepatosomatic Index (HSI) and the weight of the captured eels.

2.4. Empty Gut–Somatic Index (EGSI%):

- *Proportion of the Empty Gut–Somatic Index (EGSI%:*

According to the Empty Gut–Somatic Index (EGSI%), almost all eels captured in Lake Tonga and Wadi El Kebir were classified as silver (Fig.20).

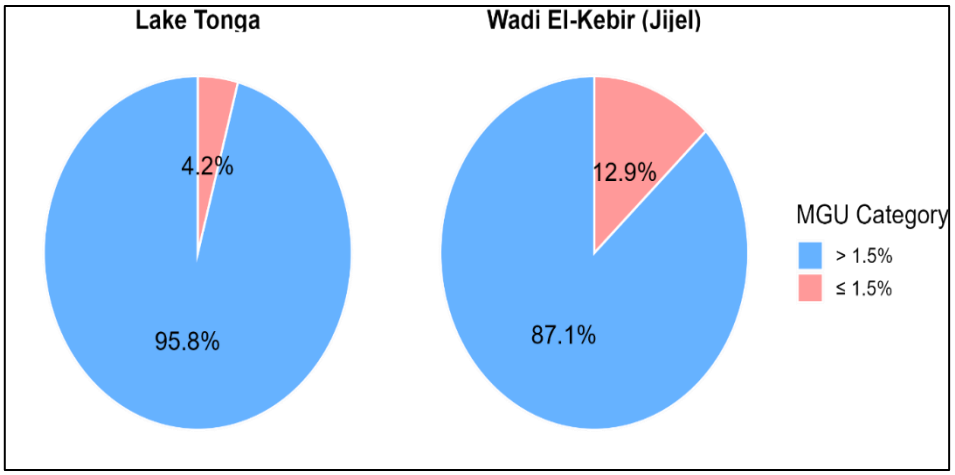

Figure 48: Proportion of EGSI% of the captured eels.

- *Seasonal variation of EGSI%:*

At Lake Tonga, the EGSI% reached its highest values in winter (~4%) and summer (~3.9%), was slightly lower in spring (~3.6%), and lowest in autumn (~2.1%). The greatest variation values were observed during autumn. At Wadi El-Kebir (Jijel), EGSI% reached its highest values in winter (~2.8%) and spring (~2.6%), was lower in autumn (~2.0%). Autumn exhibited a wider variation of values compared to winter and spring (Fig.49).

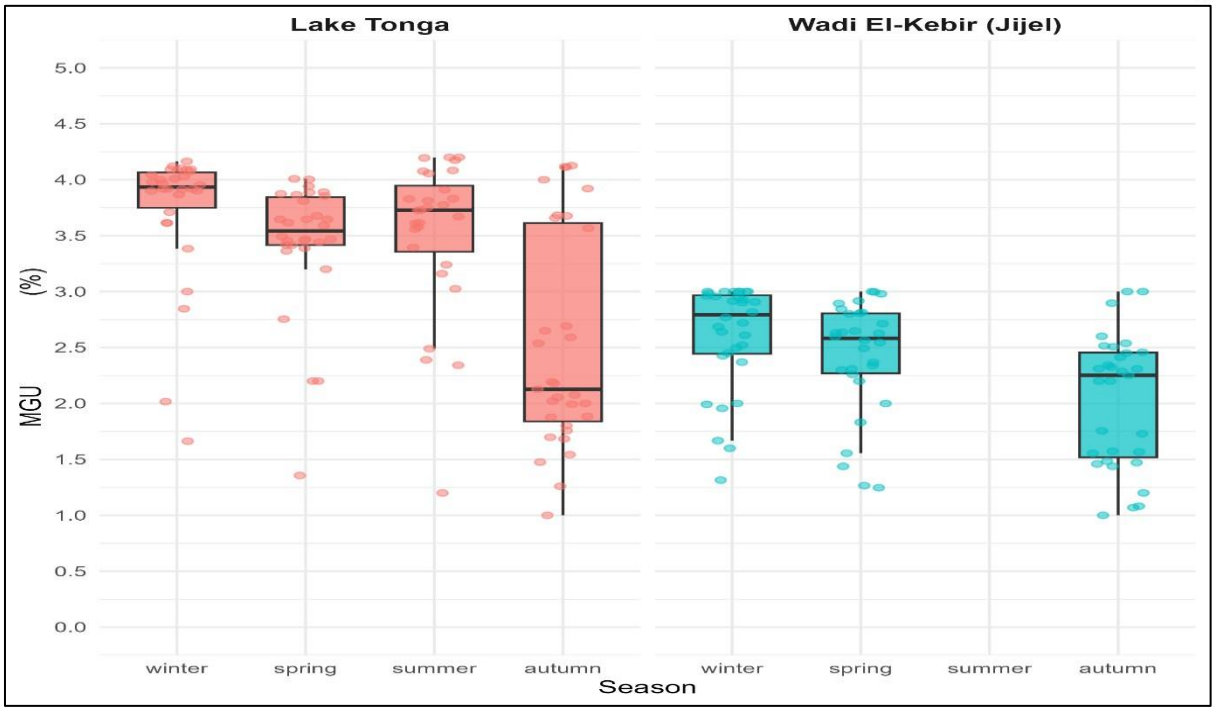

Figure 49: Seasonal variation of EGSI% of captured eels.

- *Relationship between EGSI and the weight of captured eels:*

In Lake Tonga, a weak to moderate negative relationship was observed ($R^2 = 0.26$), indicating that heavier fish tended to have lower condition. In Wadi El-Kebir, the correlation was negligible ($R^2 = 0.04$), suggesting that weight is a poor predictor of body shape in that population (Fig.50).

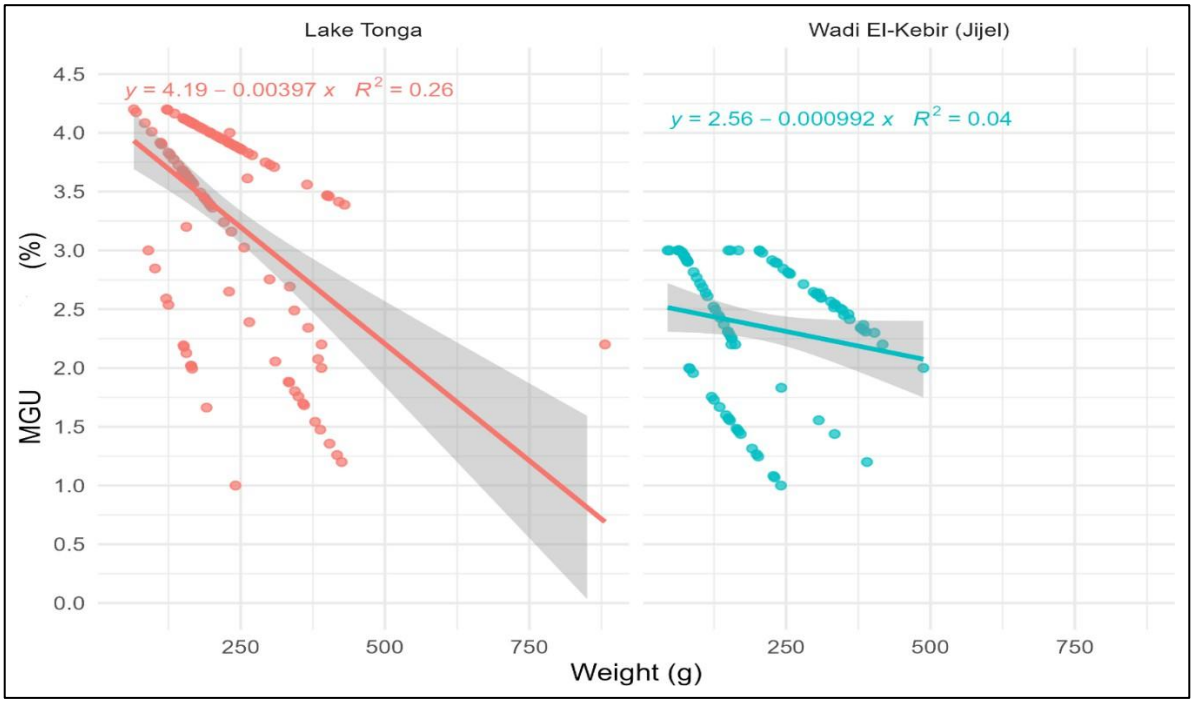

Figure 50: Relationship between EGSI and the weight of captured eels.

3. Condition Factor (K)

3.1. Seasonally variation of the mean condition factor (K):

There were noticeable seasonal variations in the condition factor (k) at both research locations. Spring (median ~2.0) and autumn (median ~2.0) had the highest values in Lake Tonga, while winter (median ~1.6, with a few higher outliers up to 2.2) saw the lowest values. With a significantly lower median (~1.7) and a much wider range (~0.7 to 4.5), summer revealed significant variations in individual's nutritional status. There was a more modest seasonal tendency in Wadi El-Kebir. The condition peaked in the spring (median ~1.9), while winter had comparable values (~1.8), with one extreme outlier at 0. The condition was at its lowest in the summer (median ~1.7), and in the fall (median ~1.8), with few fish achieving extremely low levels (~1.3) (Fig.51).

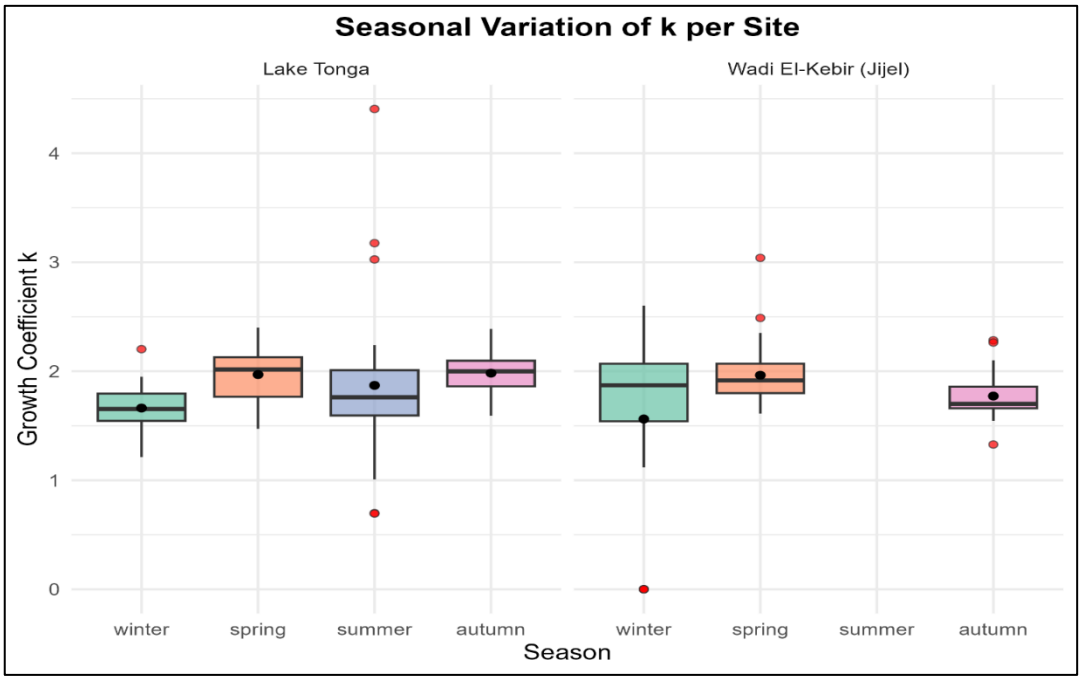

Figure 51: Seasonal variation of K of the captured eel.

3.2. Relationship between the condition factor (K) and the weight of eels:

The regression equation K = 0.157 + 0.000131 × Weight, with a coefficient of determination of $R^2 = 0.12$, describes the mild but upward trend seen in Lake Tonga in the association between Fulton's condition factor (K) and body weight. This finding suggests that weight may help improve overall body condition, as individuals with higher weights tended to have slightly higher condition levels. The model's limited explanatory power, however, highlights that weight accounts for only 12% of the variance in K. At Wadi El-Kebir (Jijel), the relationship between Fulton's condition factor (K) and body weight was found to be negligible, as indicated by the regression equation K = 0.187 + 0.0000387 × Weight, and a very low coefficient of determination ($R^2 = 0.03$). Although the slope of the regression line was slightly positive, suggesting a minor increase in K with increasing weight, the explanatory power of the model was extremely weak, with only 3% of the variation in condition factor being accounted for by weight. T (Fig.52).

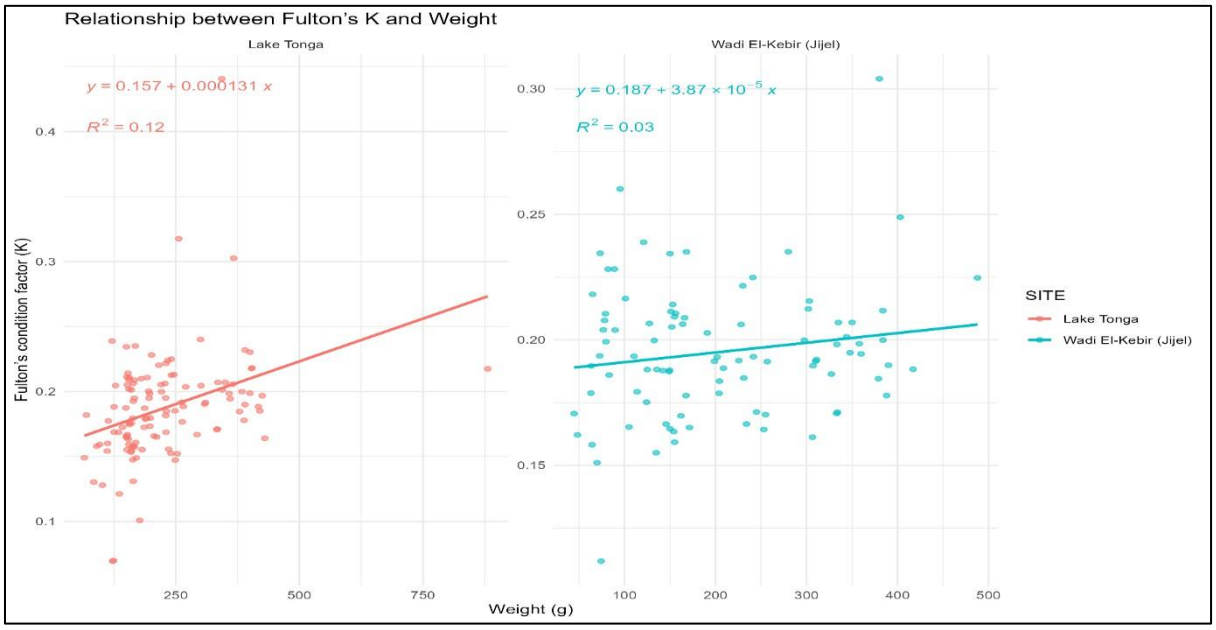

Figure 52: Relationship between the condition factor (K) and the weight of eels;

2. DIET OF SAMPLED EELS

2.1. Seasonal variations of the vacuity coefficient (CV%)

At Lake Tonga, the vacuity coefficient (CV%) was ~65% in winter, declined to ~35% in spring and ~20% in summer, then rose sharply to ~90% in autumn, indicating seasonal shifts in feeding activity (Fig.53).

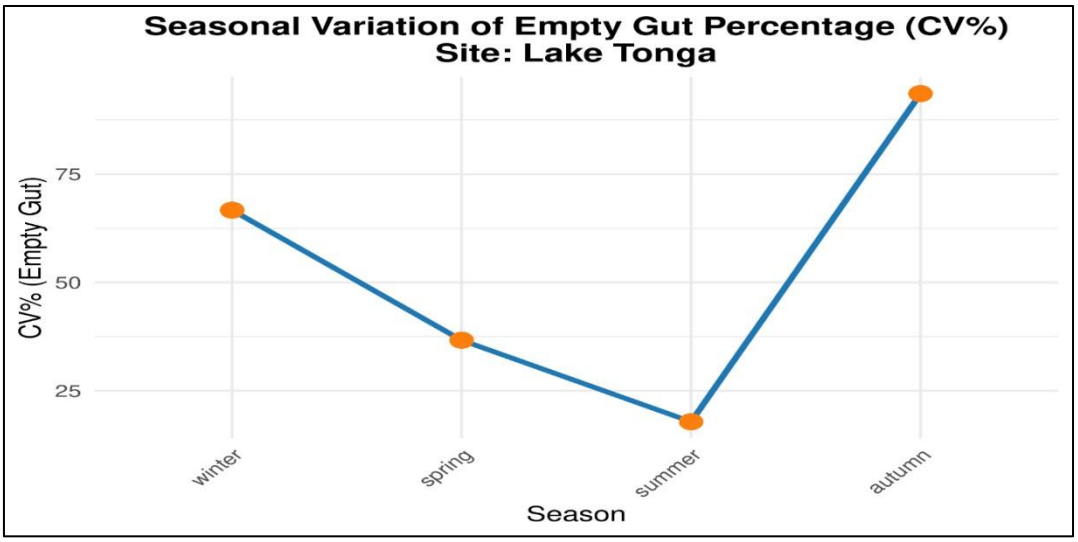

Figure 53: Seasonal variation of CV (%) the captured eel.

At Wadi El-Kebir (Jijel), empty gut percentage varied seasonally, with high values in winter (75%) and autumn (90%), indicating reduced feeding activity, while the lowest value in spring (40%) reflected increased feeding intensity. This shows that feeding activity is strongly influenced by seasonal conditions, peaking in spring (Fig.54).

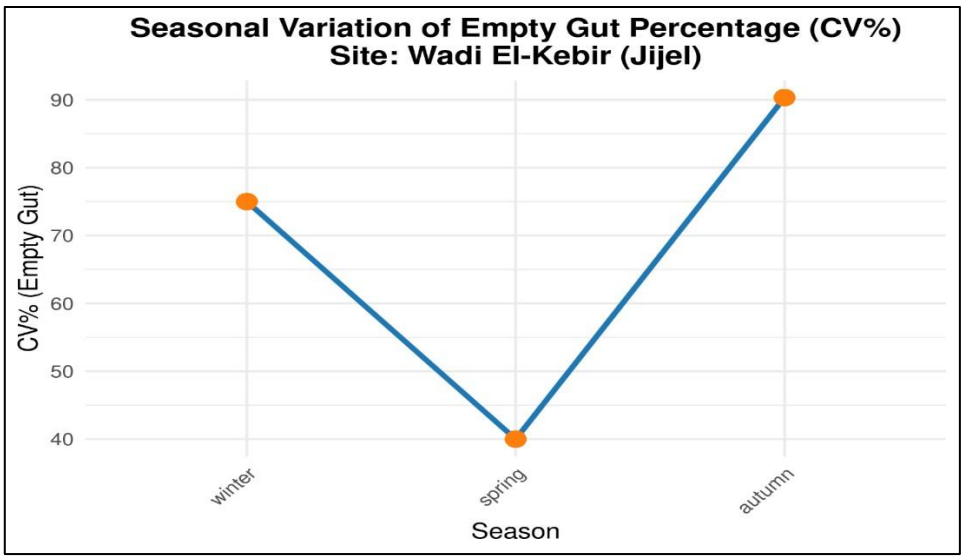

Figure 54: seasonal variation of CV (%) of the captured eel.

2.2. Variation of the Empty Gut Percentage (CV%) according to eel length classes:

Smaller fish within the 300–400 mm length class exhibited a much lower percentage of empty guts compared to other groups. In contrast, medium-length fish ranging from 400–700 mm showed relatively high and consistent empty gut percentages, falling between 55% and 60%. Interestingly, the largest class of fish (700–800 mm) recorded 0% empty guts (Fig.55).

Figure 55 : Variation of the Empty Gut Percentage (CV%) according to eel length classes at Lake Tonga.

The site Wadi El-Kebir (Jijel) shows significant variation. For the smallest length class (200-300 mm), the percentage is 0%, indicating no individuals with empty guts. This percentage rises substantially to 65.2% in the 300-400 mm length class. It further increases to 94.4% for the 400-500 mm length class, suggesting a high occurrence of empty guts in this group. Interestingly, the percentage drops to 40% in the 500-600 mm class before reaching 100% in the largest length class (600-700 mm), where all individuals have empty guts. This pattern highlights variability in feeding at different growth stages within captured fish (Fig.56).

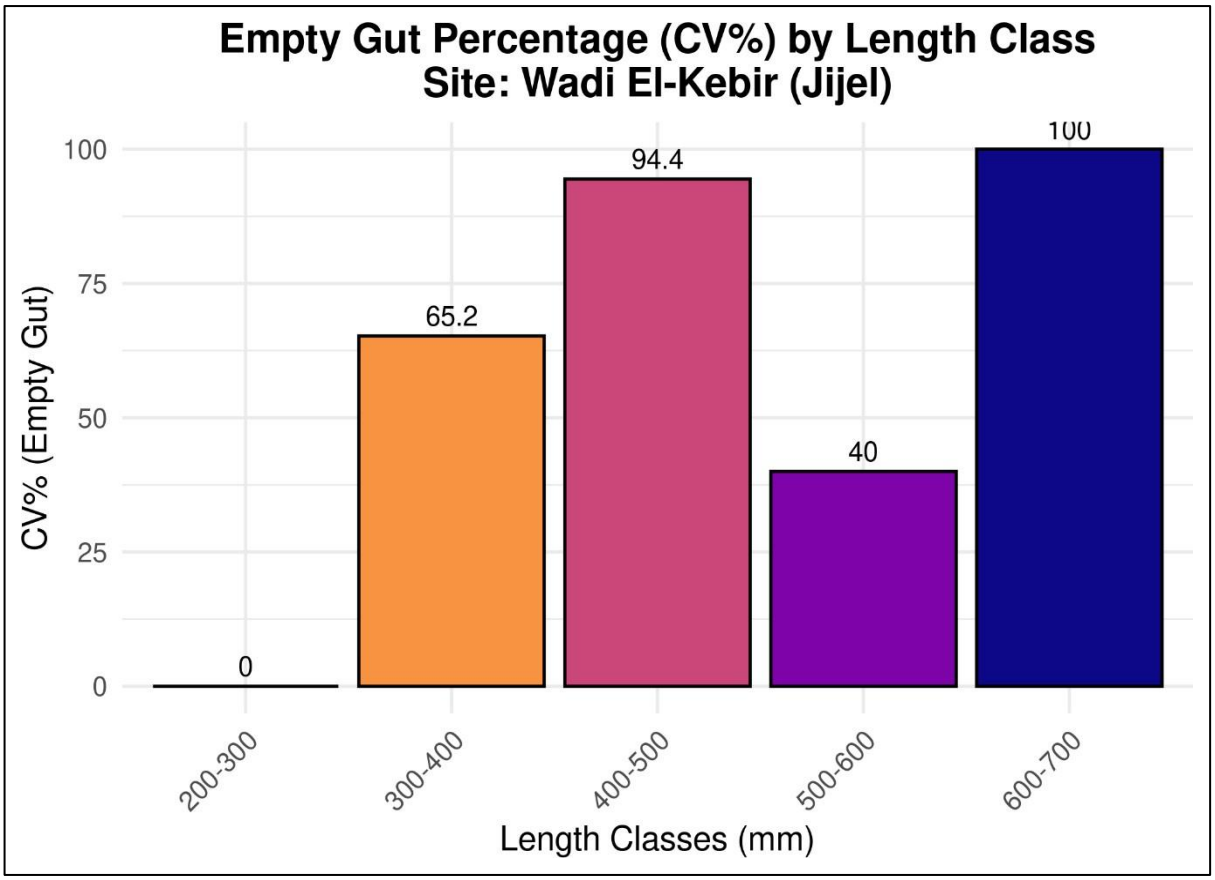

Figure 56: Variation of the Empty Gut Percentage (CV%) according to eel length classes at Wadi Elkebir

2.3. Frequency of Occurrence of Ingested Prey (F%):

The analysis of the diet composition of the European eel *Anguilla anguilla* at Lake Tonga reveals a clear dominance of fish, which represent approximately 36% of the identified prey, highlighting the species' piscivorous feeding tendency. Algae constitute the second most important dietary component with a frequency of about 23%, suggesting some degree of opportunistic herbivory. Crustaceans contribute around 12% of the total diet, while gut content of unidentified origin accounts for nearly 8%. Vegetation appears least represented, with a contribution of about 7% (Fig. 57).

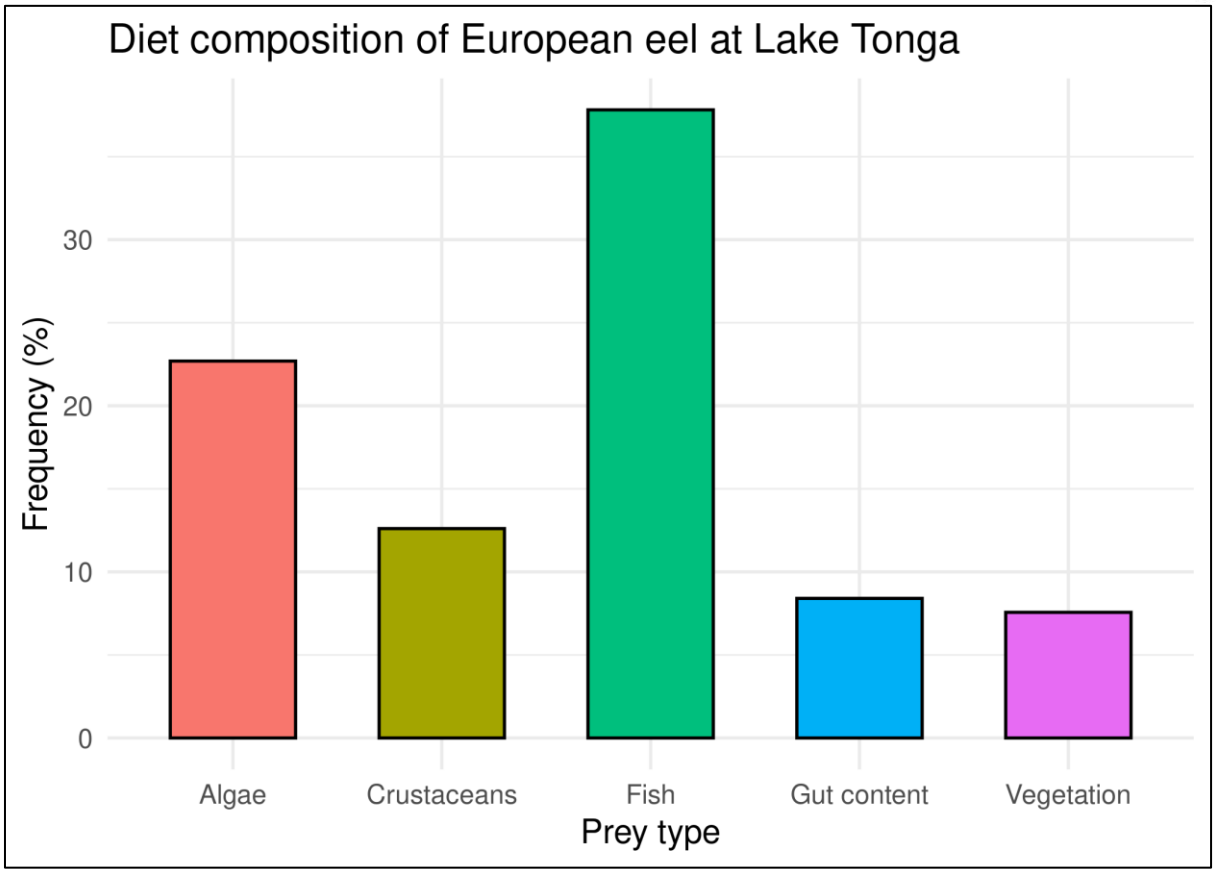

Figure 57: Frequencies of prey ingested by the eel from Lake Tonga.

Based on a study of the European eel's *Anguilla anguilla* diet at Wadi El-Kebir (Jijel), crustaceans make up around 29% of the total amount of prey consumed. At around 17%, fish make up the second most significant prey type, closely followed by algae at about 16%. About 12% is made up of vegetation, whereas the smallest percentage—nearly 9%—is made up of intestinal material of unknown origin. In contrast to the piscivorous dominance shown in Lake Tonga, our findings point to a feeding strategy where crustaceans make up a significant portion of the eels' diet in this location (Fig.58).

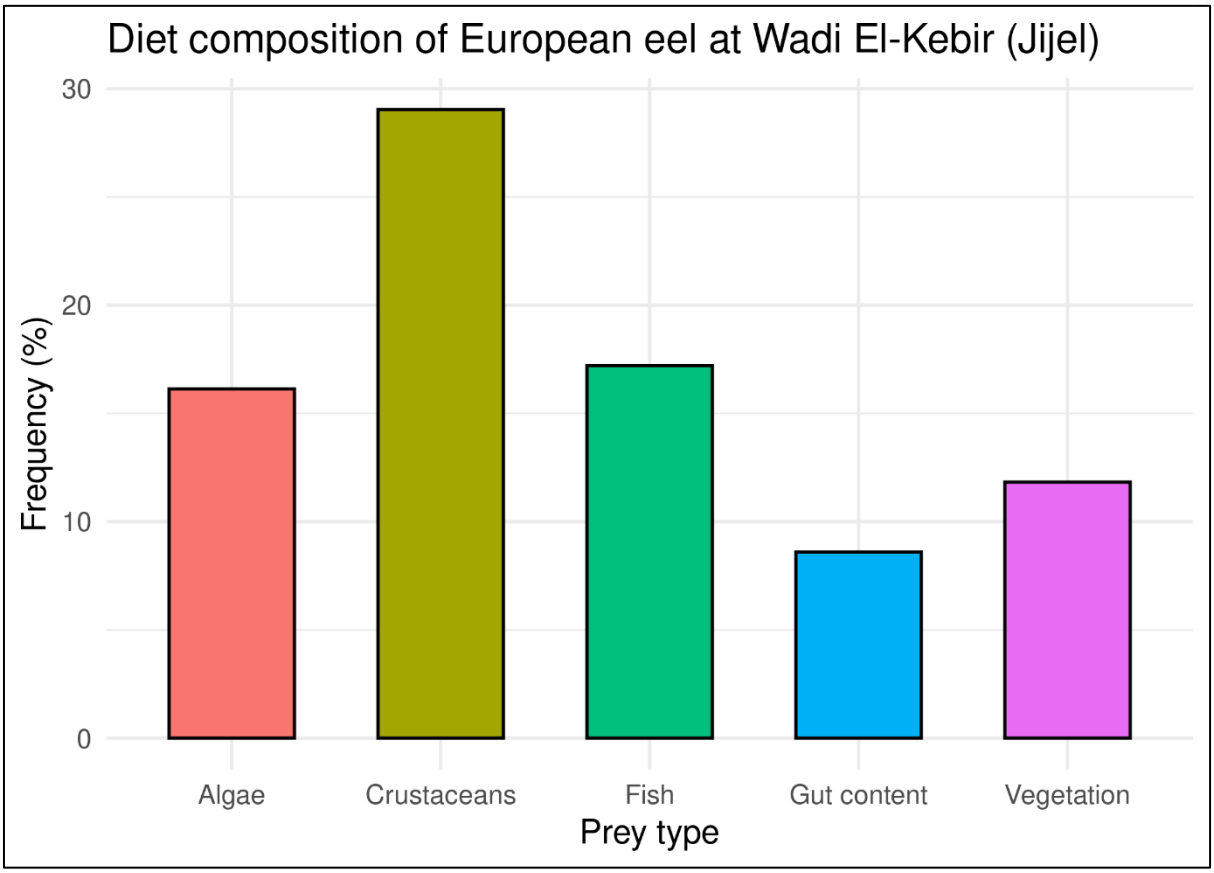

Figure 58: Frequencies of prey ingested by the eel from Wadi El-Kebir

3. OTOLITHOMETRY:

3.1. Age Distribution of Captured Eels

The analysis of age frequencies revealed marked differences in the population structure of *Anguilla anguilla* between Lake Tonga and Wadi El-Kebir (Jijel).

At Lake Tonga, the eel population is mainly composed of younger individuals, with 62.2% being one year old and 24.4% being two years old. Older individuals are relatively rare: 3-year-olds make up 3.4% of the population, while both 4-year-olds and 6-year-olds represent 0.8% each. Very young eels (<1 year) account for 10 individuals (8.4%). Overall, **the eel population in Lake Tonga is dominated by young individuals** (Table 6)**.**

The age structure in Wadi El-Kebir is more evenly distributed. 1-year-olds make up 38.7%, 2-year-olds 24.7%, and 3-year-olds 23.7%, while 4-year-olds represent 7.5%. Very young eels (<1 year) are 5 individuals (5.4%). This indicates a broader age distribution and better survival of older eels at Wadi El-Kebir (Table 6).

Table 6: Age distribution of European eel by site

Age Class	**Lake Tonga** (PNEK)		**Wadi El-Kebir (Jijel)**	
	N	**%**	**N**	**%**
<1	10	8.4	5	5.4
1	74	62.2	36	38.7
2	29	24.4	23	24.7
3	4	3.4	22	23.7
4	1	0.8	7	7.5
6	1	0.8	0	0.0

3.2. Growth Modelling Based on Length Data:

The Von Bertalanffy Growth Function (VBGF) applied to European eel (*Anguilla anguilla*) from Lake Tonga shows a good fit between observed lengths and the modeled growth curve (Fig. 59). The estimated parameters are: $L\infty$=740 mm, K=0.4year−1, and t0=−1.0.
These values indicate rapid growth during the early life stages (0–2 years), when individuals reach ~350–500 mm, followed by a progressive slowdown as eels approach the theoretical

maximum length of 740 mm. The relatively high growth coefficient reflects favorable environmental conditions in the lake, allowing eels to attain substantial length within a few years. Despite individual variability, the model provides a reliable description of the population's growth trajectory.

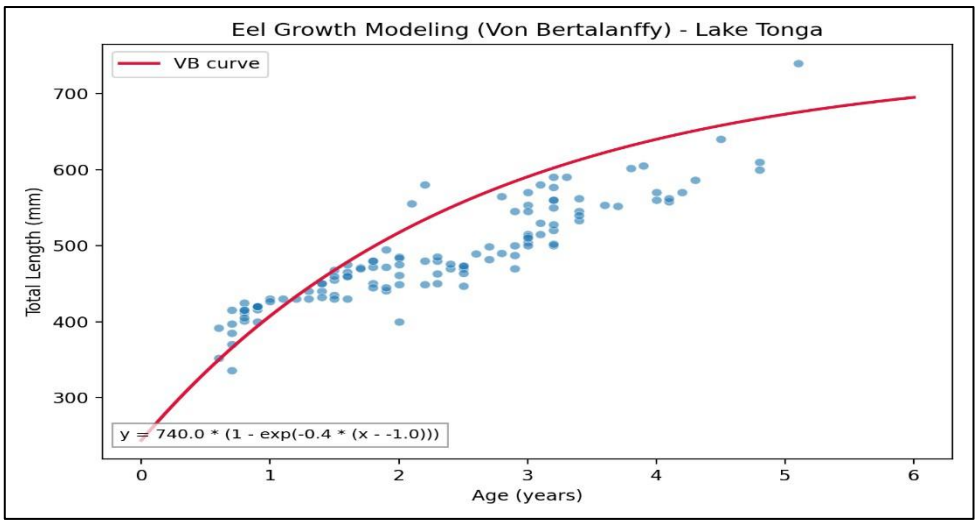

Figure 59: Von Bertalanffy Growth Modelling of Captured Eels from lake Tonga

The estimated parameters of the eel population in Wadi El-Kebir are: L∞=790.98 mm, K=0.26 year−1, and t0=−1.225years. The negative t0 represents a mathematical adjustment commonly applied to improve curve fitting and does not imply a real negative age. The model highlights a rapid initial growth phase in juvenile eels, followed by a progressive slowdown as individuals approach their maximum theoretical length, reflecting the principles of energy allocation and metabolic constraints on growth. The close agreement between the observed data and the fitted curve demonstrates the model's suitability for describing growth patterns in this ecological context (Fig. 60).

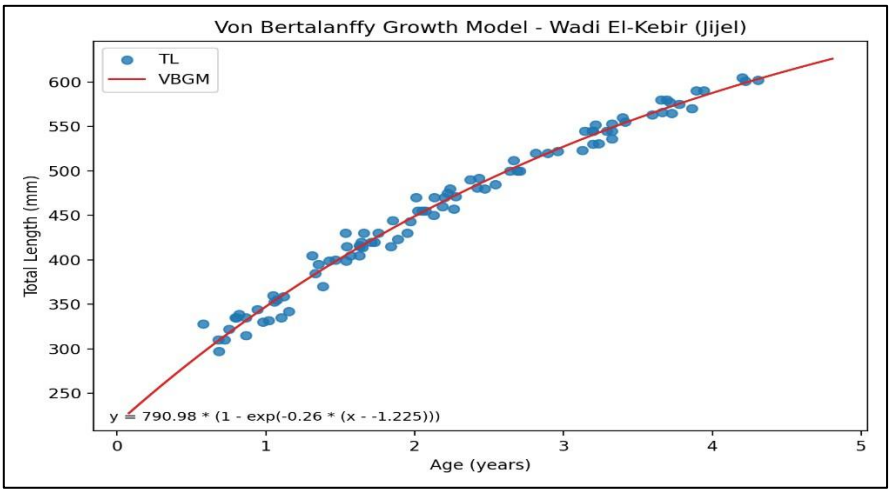

Figure 60: Von Bertalanffy Growth Modelling of Captured Eels from Wadi el Kebir, Jijel

3.3. Growth Modelling Based on Weight Data:

- **Lake Tonga**

The regression analysis of log-transformed weight against age for eels from Lake Tonga revealed a strong positive relationship ($r = 0.88$, $p < 0.001$). The linear model ($\log W = 4.73 + 0.32A; R^2 = 0.77$)indicates an overall exponential increase in weight with age, corresponding to an average annual weight gain of approximately 38 %. The quadratic model ($\log W = 4.61 + 0.42A - 0.03A^2; R^2 = 0.81$) provided a superior fit, capturing a slight deceleration in growth among individuals older than four years (Fig. 61)..

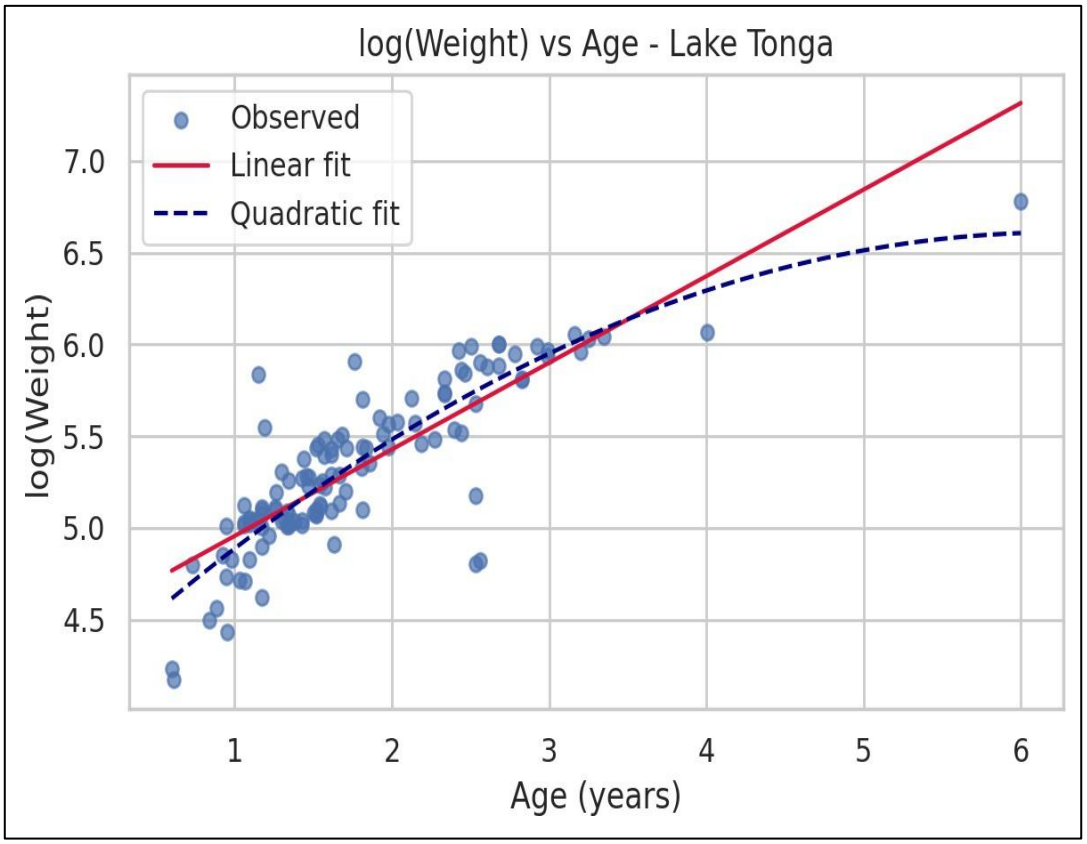

Figure 61: Growth Modelling Based on log Weight Data of captured eel from Tonga Lake.

- **Wadi el kebir jijel:**

Data show that weight increases with age but not at a constant rate; the quadratic fit reveals a more realistic model for growth, capturing both the initial acceleration and eventual plateau phase seen in many biological systems (Fig. 62).

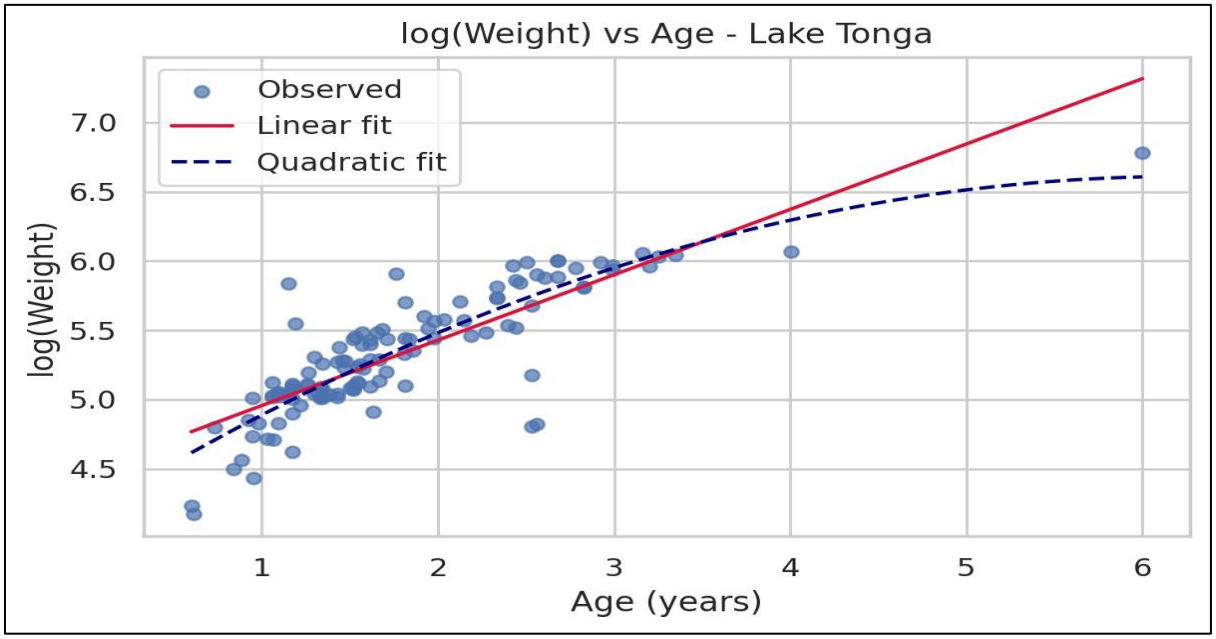

Figure 62: Growth Modelling Based on log Weight Data of captured eel from Wedi El Kebir, Jijel.

3.4. Semi-structured qualitative validation

Lake Tonga's edge type remains predominantly opaque throughout all seasons, with more than 90% opacity in winter, spring, summer, and autumn. Translucency is consistently low, only rising slightly to about 10% in autumn. (Fig. 63).

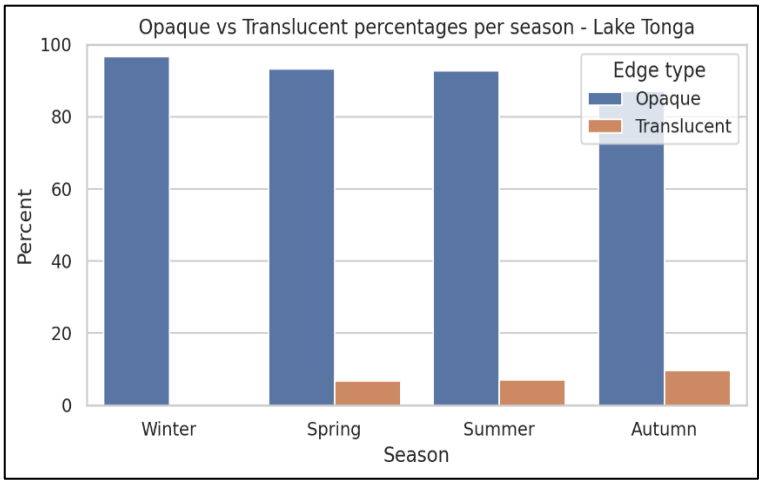

Figure 63: Evolution of the percentage of opaque and translucent edges of otoliths at Lake Tonga

❖ **Wadi El-Kebir (Jijel):**

The opaque edges dominate in all seasons, comprising approximately 78% to 94% of the total. The highest percentage of opaque edges is seen in winter (~94%), while the lowest occurs in autumn (around 78%). Conversely, translucent edges make up a smaller portion, increasing from about 6% in winter to 22% in autumn. (Fig. 64).

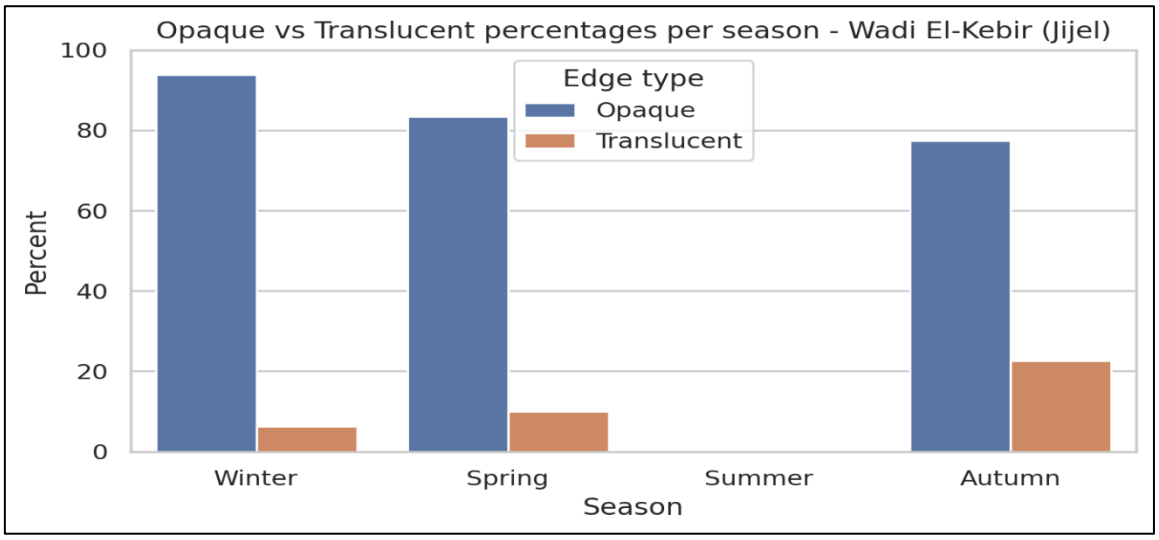

Figure 64: Evolution of the percentage of opaque and translucent edges of otoliths Wadi El-Kebir Jijel.

3.5. Relationship Between Eel Age and the Eye Index

❖ **For Wadi El-Kebir:**

The linear regression equation is $y = 5.913 + 0.407x$, with a coefficient of determination $R^2 = 0.05$. This indicates a very weak positive correlation between age and ocular index, where age accounts for only about 5% of the observed variation. Thus, the predictive power of age on ocular index in this population is minimal.

❖ **For Lake Tonga:**

The regression line is estimated as $y=6.237+0.919x$, showing a steeper positive slope compared to Wadi El-Kebir. The coefficient of determination R2 is notably higher, suggesting that age explains a larger portion of the variation in ocular index. (Fig. 65).

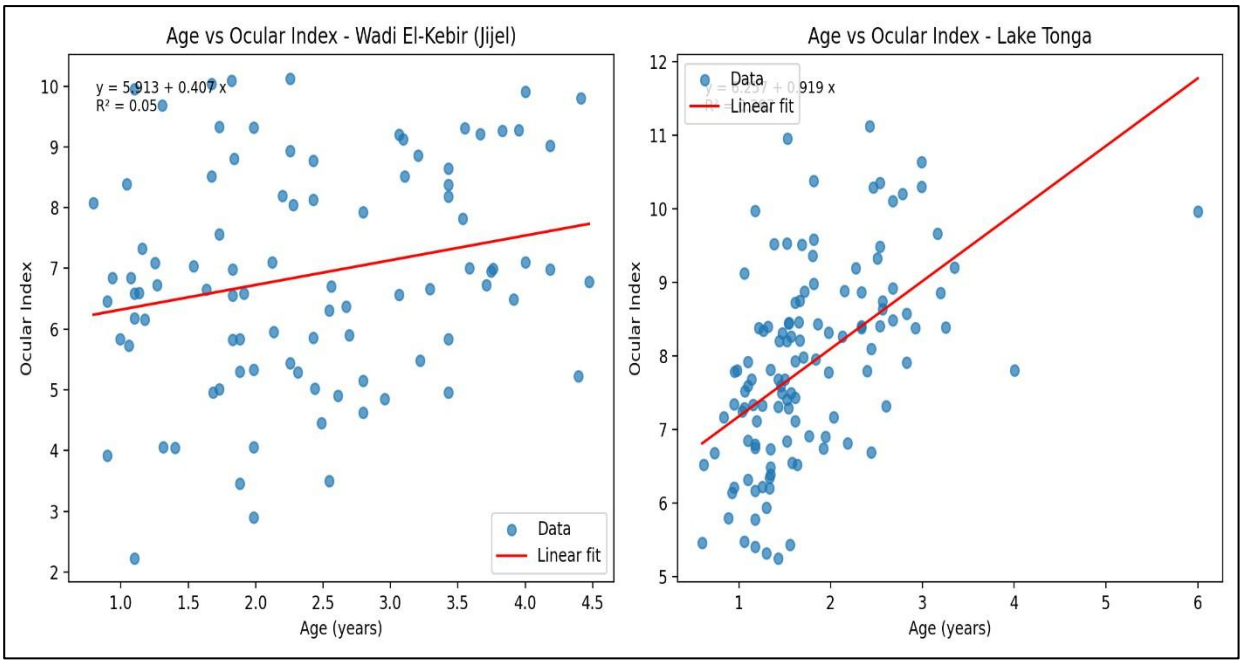

Figure 65: Age and ocular index of the captured eels

3.6. Relationship Between Eel Age and GSI:

This analysis provides insights into reproductive maturity dynamics and allows comparison of how different eel populations allocate resources to reproduction over their lifespan by relating age (years) to the Gonadosomatic Index (GSI).

- At Wadi El-Kebir, a moderate positive correlation is observed between Age and GSI, with a linear fit equation of approximately y=-0.396+0.526x, indicating GSI tends to increase as fish age.
- At Lake Tonga, the positive trend is also clear, with a linear fit equation roughly y=0.101+0.397x, showing gonadal development increases with age here as well.
- The slopes suggest gonadal development is somewhat faster or more pronounced with age at Wadi El-Kebir than at Lake Tonga.
- The spread around each fit line indicates other environmental or biological factors besides age that impact GSI variability.

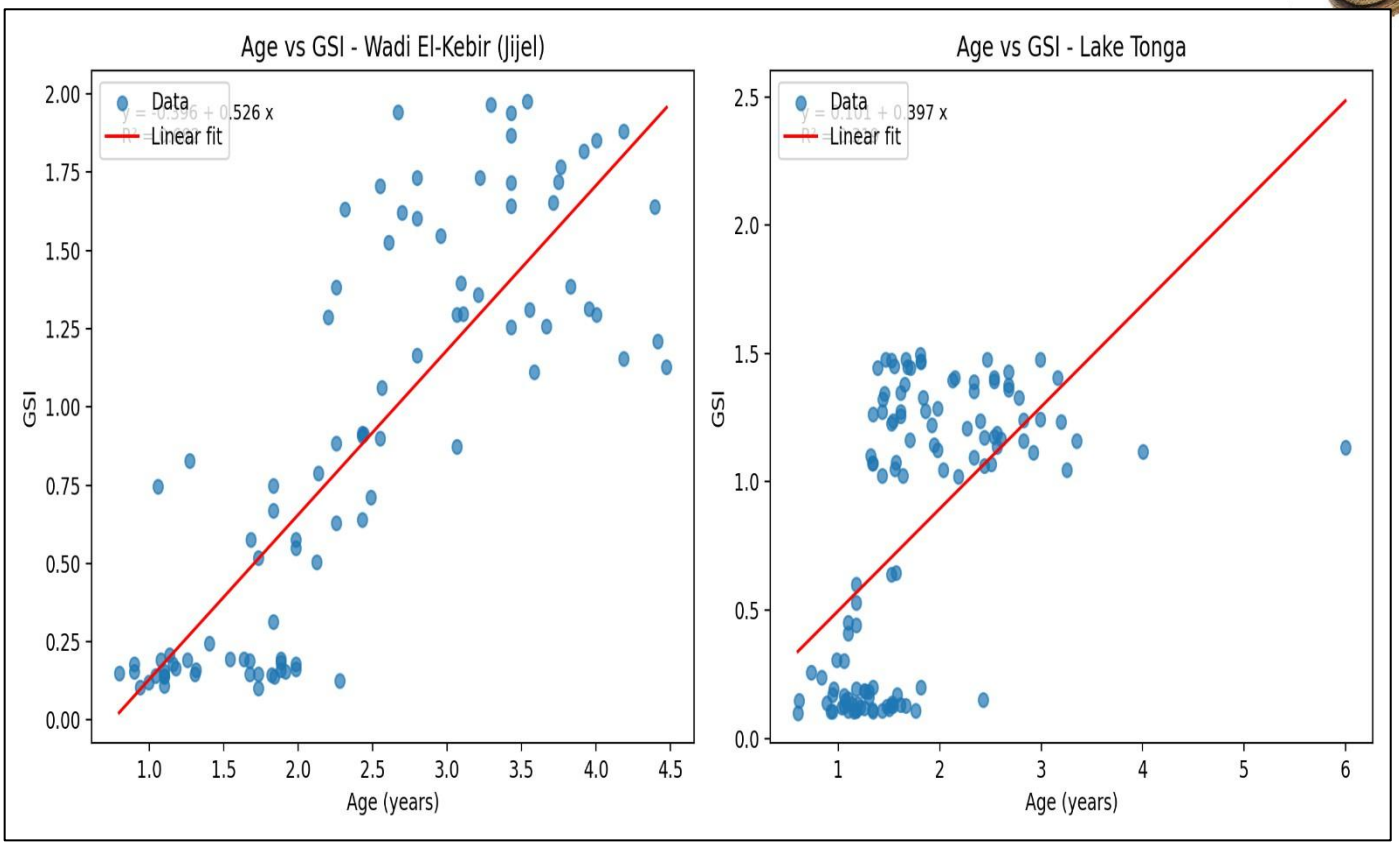

Figure 66: Relationship Between Eel Age and GSI of captured eels

4. PARASITISM

4.1. Parasites Recorded:

The assessment of the parasitic fauna of eels captured in Lake Tonga and Wadi El-Kebir (Jijel) revealed a total of **1,496 parasites** belonging to six species. The parasitic community was composed of *Bothriocephalus claviceps*, located in the digestive tract; *Hysterothylacium* sp., found in both the muscle and the digestive tract; and *Anguillicoloides crassus*, inhabiting the swim bladder. At the level of the gills, three additional taxa were identified: two crustaceans, *Ergasilus gibbus* and *Argulus* sp., and one monogenean, *Pseudodactylogyrus* sp. (Table.7).

A single crustacean copepod *(Ergasilus gibbus)* was identified during this study.

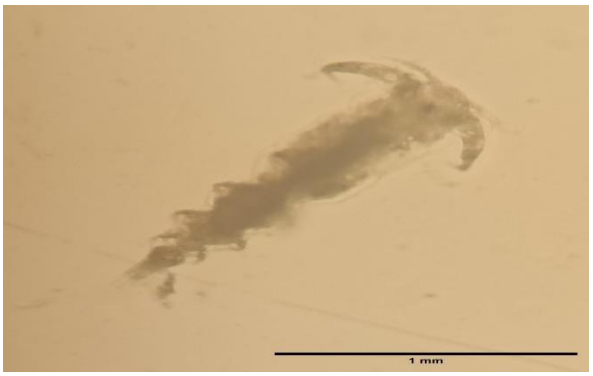

Figure 67: Photograph of Ergasilus sp. observed during this study (Boughaba, 2021).

Another crustacean, *Argulus* sp., belonging to the subclass Branchiura, was recorded but proved to be far less abundant than *Ergasilus gibbus*.

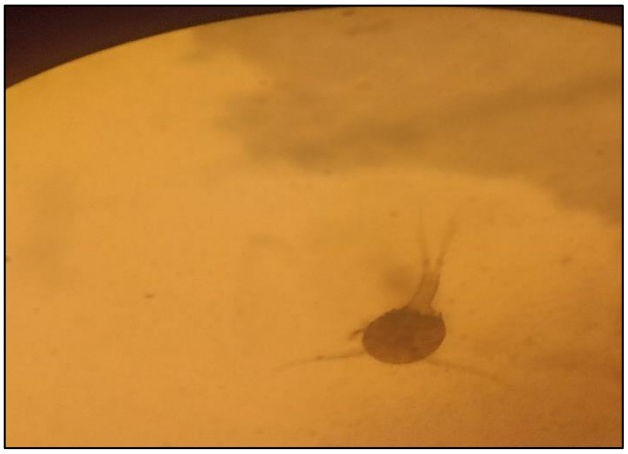

Figure 68 : Photograph of Argulus sp. observed during this study (Boughaba, 2021).

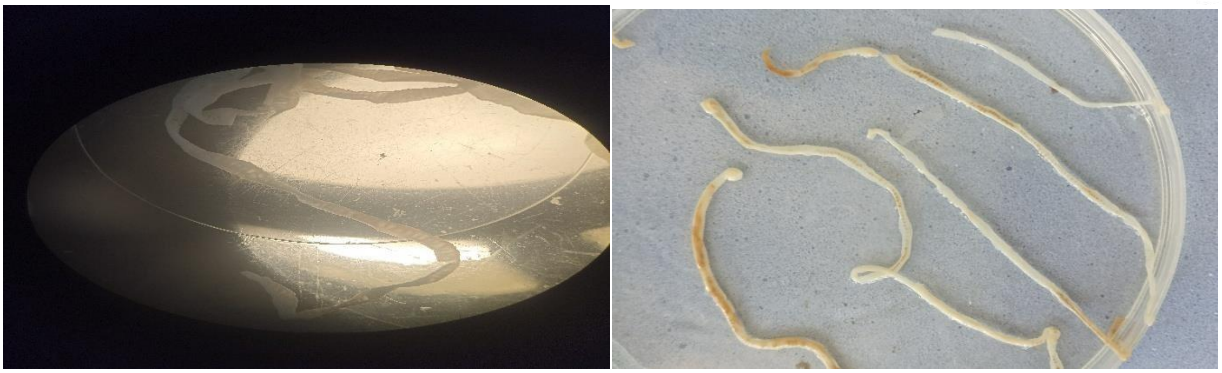

Figure 69 : Photograph of *bothriocephalus claviceps*. observed during this study (Boughaba, 2021).

During this thesis, two nematode species were recorded: *Anguillicoloides crassus*, found in the swim bladder

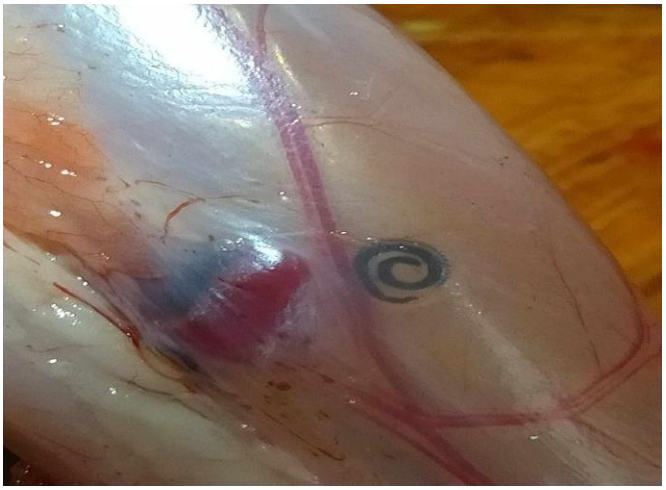

Figure 70: *Anguillicoloides crassus*, found in the swim bladder (Boughaba, 2021).

Hysterothylacium sp., was generally found encysted in the muscle and digestive tract of the sampled eels

Figure 71: Photograph of *Hysterothylacium* sp. encysted in the digestive tract observed during the present study (Boughaba, 2019).

Table 7 : Epidemiological parameters: Prevalence (P%), Abundance (A), and Mean Intensity (I) of parasites recorded in eels from Lake Tonga and Wadi El-Kebir (Jijel).

Parasite Infection Summary per Site												
	Lake Tonga						Wadi El-Kebir (Jijel)					
	N examined	**N parasites**	**N infected**	**P (%)**	**I**	**A**	**N examined**	**N parasites**	**N infected**	**P (%)**	**I**	**A**
Anguillicoloides crassus	119	236	68	57.1	3.47	1.98	93	189	57	61.3	3.32	2.03
Argulus sp	119	63	31	26.1	2.03	0.53	93	22	17	18.3	1.29	0.24
Bothriocephalus claviseps	119	88	45	37.8	1.96	0.74	93	83	37	39.8	2.24	0.89
Ergasilus gibus	119	96	48	40.3	2.00	0.81	93	99	58	62.4	1.71	1.06
Hysterothylacium sp	119	103	45	37.8	2.29	0.87	93	37	26	28.0	1.42	0.40
Pseudodactylogyrus sp	119	282	76	63.9	3.71	2.37	93	198	59	63.4	3.36	2.13

4.2. Summary of parasitological indices:

❖ Prevalence:

The prevalence analysis revealed a clear dominance of the monogenean *Pseudodactylogyrus* sp., occurring in 63.9% of eels from Lake Tonga and 63.4% from Wadi El-Kebir. The second most prevalent parasite was the swim bladder nematode *Anguillicoloides crassus*, infecting more than half of the sampled individuals. Additional taxa recorded with notable frequencies were the crustaceans *Ergasilus gibbus* and *Argulus* sp., along with the intestinal cestode *Bothriocephalus claviceps* and the nematode *Hysterothylacium* sp. (Fig.72).

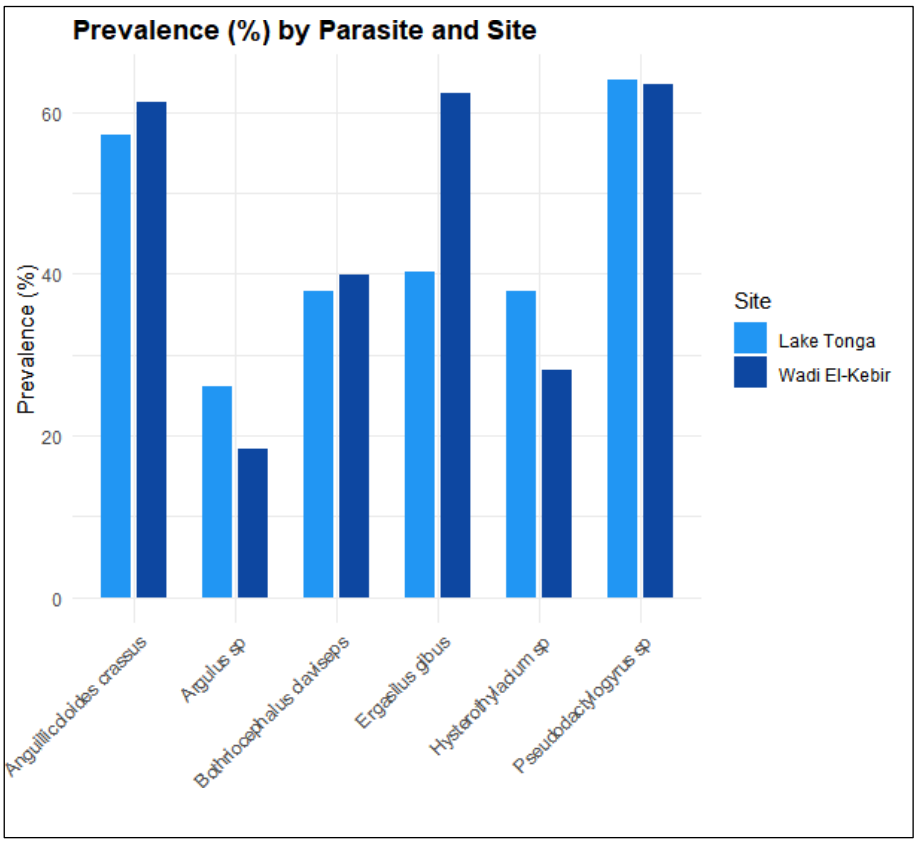

Figure 72: Prevalence (P%), of parasites recorded in eels from Lake Tonga and Wadi El-Kebir (Jijel).

❖ Intensity:

The analysis of mean intensity revealed a clear predominance of the monogenean *Pseudodactylogyrus* sp., with average parasite loads of 3.71 individuals per infected eel in Lake Tonga and 3.36 in Wadi El-Kebir. The swim bladder nematode *Anguillicoloides crassus* was

the second most dominant species, exhibiting mean intensities of 3.47 and 3.32 in the respective site (Fig.73).

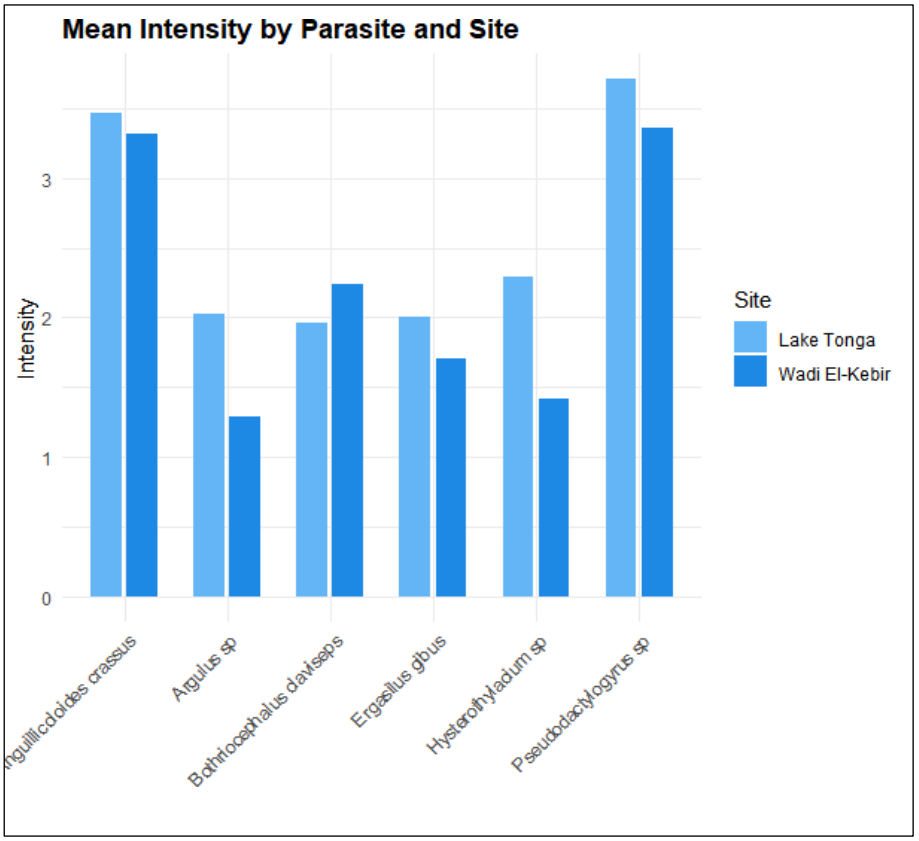

Figure 73: mean intensity of parasites recorded in eels from Lake Tonga and Wadi El-Kebir (Jijel).

❖ **Abundance:**

In terms of abundance, the monogenean *Pseudodactylogyrus* sp. was recorded at an average of 2.37 parasites per eel in Lake Tonga and 2.13 in Wadi El-Kebir. Among the helminths, the swim bladder nematode *Anguillicoloides crassus* displayed the highest abundance, with mean values of 1.98 and 2.03 parasites per eel in Lake Tonga and Wadi El-Kebir, respectively. Gill-associated parasites showed the lowest abundance, with mean values consistently below one parasite per gill throughout the study period (Fig.74).

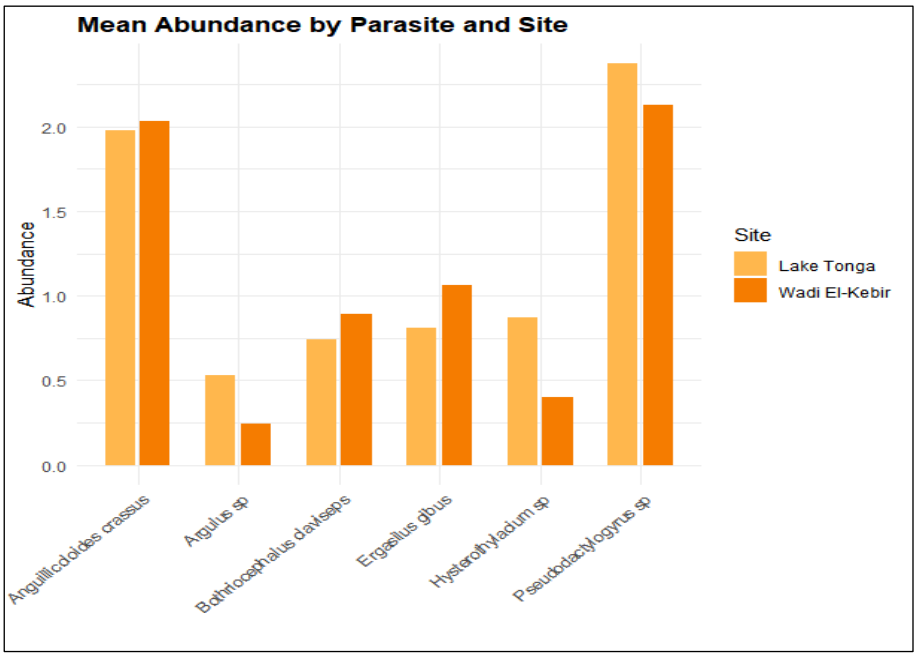

Figure 74: Abundance of parasites recorded in eels from Lake Tonga and Wadi El-Kebir (Jijel).

5.3.1. Seasonal distribution of parasitological indices of *Hysterothylacium* sp. in Lake Tonga:

- **Prevalence:**

The seasonal assessment of infestation rates of eels by the nematode *Hysterothylacium* sp. indicated that prevalence generally ranged from 30% to 60%. However, during winter, the infection level declined markedly, affecting fewer than 10% of the sampled individuals (Fig.75).

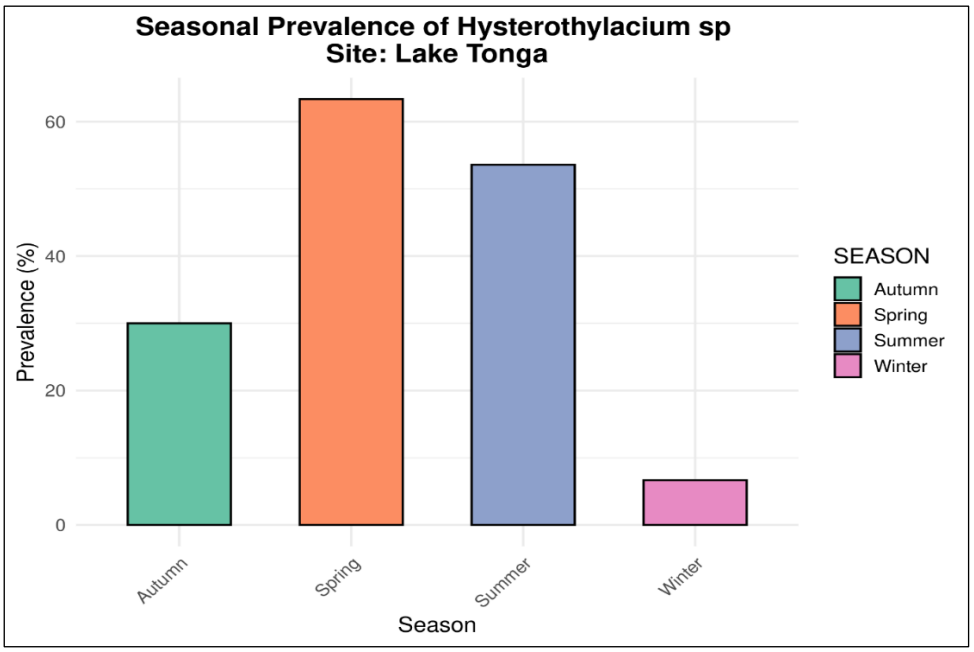

Figure 75: seasonal prevalence of *Hysterothylacium sp*. in lake Tonga

❖ **Mean intensity and abundance:**

The seasonal dynamics of *Hysterothylacium* sp. infestation in eels from Lake Tonga showed marked variation, with peak values in spring (mean intensity ≈3.3; abundance ≈2.1), moderate levels in summer (1.8; 0.9), and lower values in autumn (1.3; <0.5). Winter was characterized by the lowest abundance (≈0.1) despite a moderate intensity (≈1.5), indicating that parasite transmission is highest in spring and declines progressively towards winter. (Fig.76).

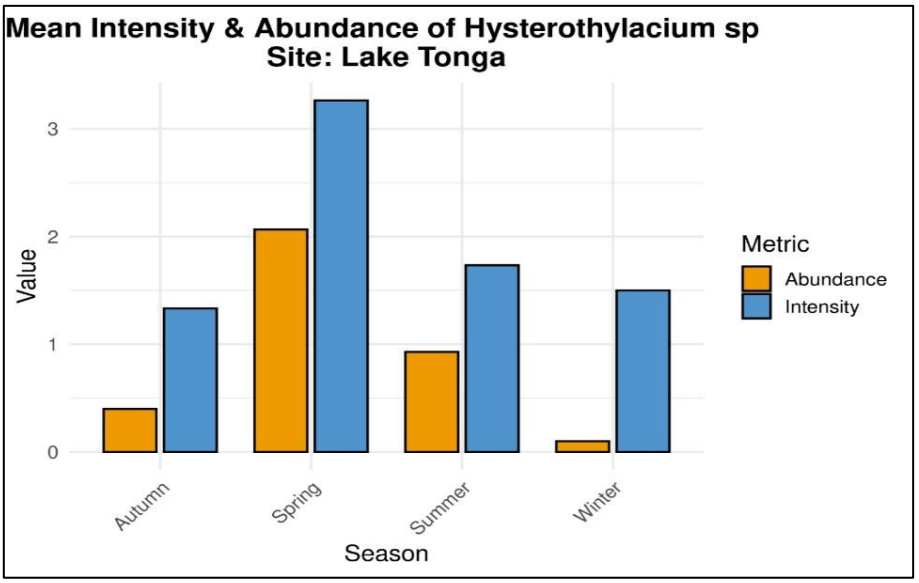

Figure 76: Seasonal intensity and abundance of *Hysterothylaciam* sp.in lake Tonga

4.2.1. Seasonal distribution of parasitological indices of *Hysterothylacium* sp. In Wadi El-Kebir (Jijel):

- **Prevalence:**

The prevalence of *Hysterothylacium* sp. in eels from Wadi El-Kebir exhibited clear seasonal variation. The highest prevalence was observed in spring (≈43%), followed by autumn (≈30%), while the lowest level occurred in winter (≈13%). This pattern highlights a marked seasonal effect, with infestation peaking in spring and declining progressively towards winter.(Fig.77).

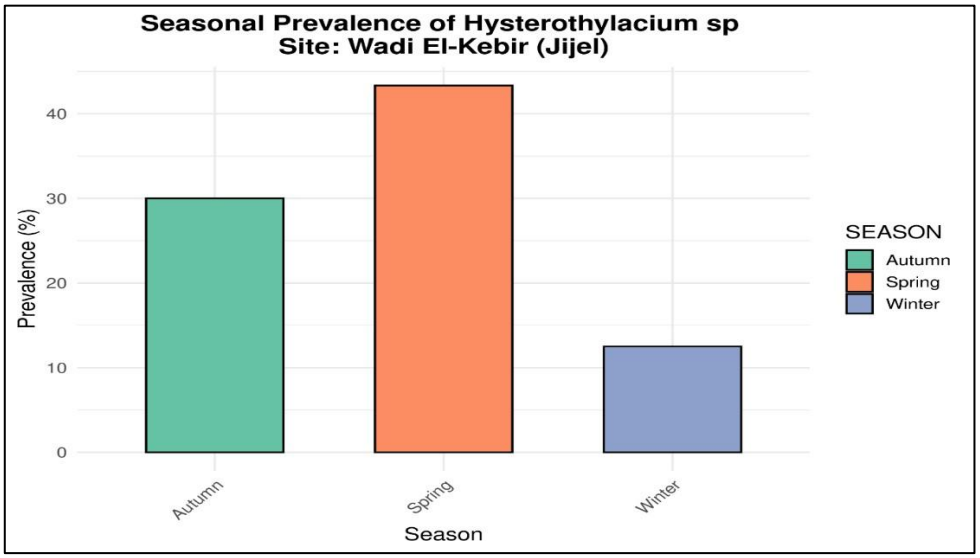

Figure 77: seasonal prevalence *Hysterothylacium sp*.in Wadi El-Kebir (Jijel)

❖ **Intensity and abundance:**

The mean intensity and abundance of *Hysterothylacium sp* at Wadi El-Kebir (Jijel) varied noticeably across seasons. In spring, both parameters reached their highest levels, with mean intensity around 1.55 and abundance approximately 0.7, indicating optimal conditions for parasite transmission. During autumn, moderate values were recorded, with mean intensity about 1.3 and abundance near 0.35, reflecting ongoing but reduced infection rates. In winter, mean intensity remained moderate at 1.3, while abundance dropped sharply to around 0.15, suggesting that although fewer fish were infected, those infected harbored multiple parasites. Overall, these results highlight a strong seasonal influence, with spring emerging as the peak period of *Hysterothylacium sp* infection**.**(Fig.78).

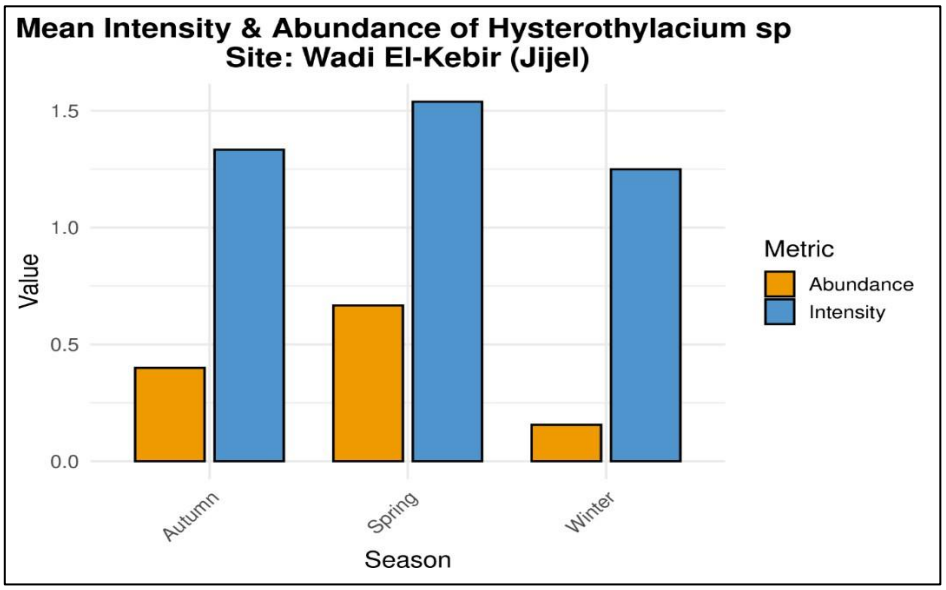

Figure 78: The mean intensity and abundance of *Hysterothylacium sp* at Wadi El-Kebir

4.2.2. Seasonal Distribution of Parasitological Indices of *Hysterothylacium* sp. according to length Classes at lake Tonga:

❖ **Prevalence:**

The prevalence of *Hysterothylacium sp.* in Lake Tonga showed a clear increase with fish length. In smaller fish (300–400 mm), prevalence was relatively high at about 65%, indicating early exposure to the parasite. A noticeable decrease occurred in the 400–500 mm class, where prevalence dropped to around 22%, possibly reflecting variation in feeding habits or sample size. From 500–600 mm onward, prevalence rose again to approximately 53%, and reached

100% in both the 600–700 mm and 700–800 mm classes, showing that all larger fish were infected. (Fig.79).

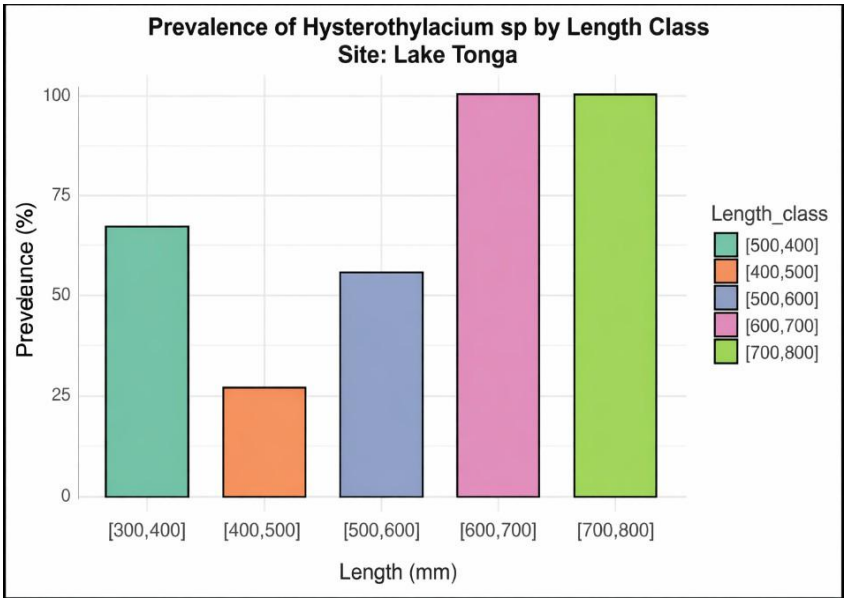

Figure 79: The prevalence of *Hysterothylacium sp.* by length classes in lake Tonga.

❖ **Intensity and abundance:**

The mean intensity and abundance of *Hysterothylacium* sp. in fish from Lake Tonga show a clear increasing trend with fish length. In the smaller size classes (300–500 mm), infection levels are relatively low, with mean intensity slightly higher than abundance. As fish length increases (500–700 mm), both parameters rise moderately and reach similar values, suggesting a gradual accumulation of parasites. The largest length class (700–800 mm) exhibits the highest values for both mean intensity and abundance, around seven, indicating that larger fish harbor more parasites and experience more intense infections. (Fig.80).

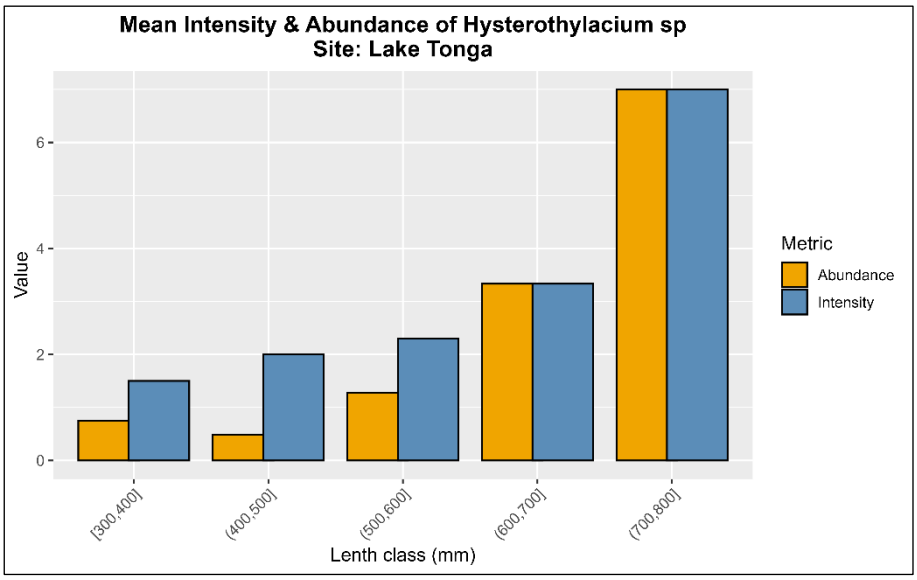

Figure 80: The mean intensity and abundance of *Hysterothylacium* sp. by length classes in lake Tonga.

4.2.3. Seasonal distribution of parasitological indices of *Hysterothylacium* sp. in Wadi El-Kebir (Jijel) according to length class:

❖ **Prevalence:**

This pattern indicates a strong positive relationship between fish length and parasite prevalence. Larger fish are more likely to be infected, reaches 100% prevalence, meaning that all individuals in this length group were infected**.**(Fig.81).

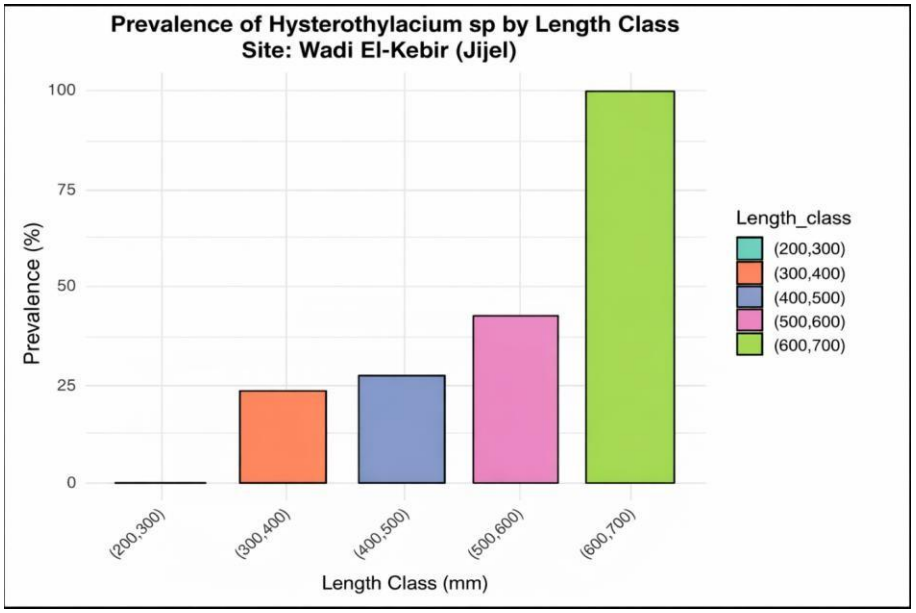

Figure 81: The prevalence of *Hysterothylacium sp.* in Wadi El-Kebir (Jijel) according to length class.

❖ **Mean intensity and abundance:**

The mean intensity and abundance of *Hysterothylacium* sp. in Wadi El-Kebir (Jijel) increased progressively with fish length. No infection was recorded in the smallest length class (200–300 mm). In the 300–400 mm and 400–500 mm classes, mean intensity ranged between 1.2 and 1.4, while abundance remained low (around 0.2–0.3). In fish measuring 500–600 mm, mean intensity reached about 1.5 and abundance about 0.6, indicating a moderate increase. The highest values were observed in the largest length class (600–700 mm), where both mean intensity and abundance reached approximately 2.0, showing that larger fish harbored more parasites and experienced more intense infection. (Fig.82).

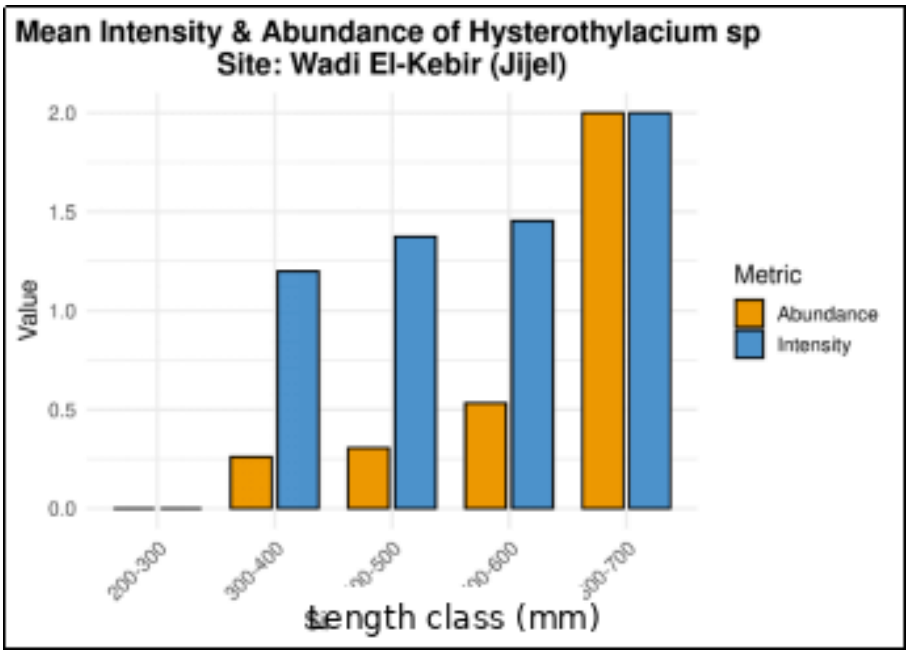

Figure 82: The mean intensity and abundance of *Hysterothylacium* sp. in Wadi El-Kebir (Jijel) by length classes.

4.2.4. Seasonal distribution of parasitological indices of *Bothriocephalus Claviceps in* Lake Tonga:

❖ **Prevalence:**

The seasonal prevalence of *Bothriocephalus claviseps* at Lake Tonga varies throughout the year. In spring, the prevalence is highest at about 50%. Winter follows with a prevalence near 43%. Autumn has a moderate prevalence of around 28%, while summer shows the lowest

prevalence at approximately 23%. This indicates that the parasite is most common in the warmer seasons, especially spring, and least common in summer at this location. (Fig.83).

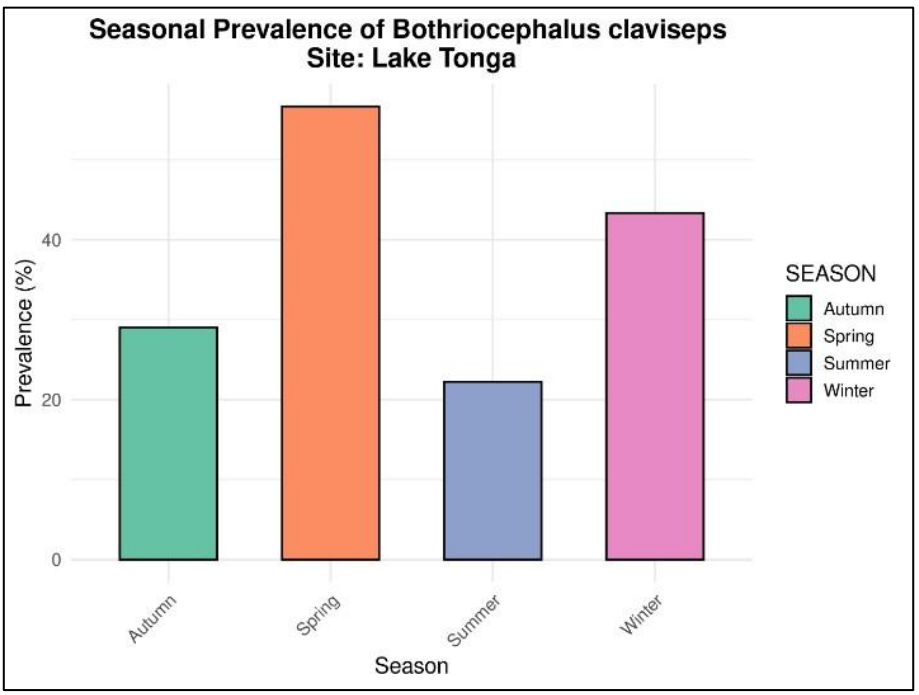

Figure 83: The seasonal prevalence of *Bothriocephalus claviseps* at Lake Tonga.

❖ **Mean intensity and abundance:**

The mean intensity and abundance of *Bothriocephalus claviseps* at Lake Tonga vary by season. Intensity is highest in winter, with a value of 3, followed by spring at approximately 1.6. Autumn has an intensity of about 1.5, while summer is the lowest at around 1.2. Regarding abundance, winter again shows the highest value at roughly 1.35, followed by spring with about 0.9. Autumn has an abundance near 0.4, and summer is the lowest at approximately 0.3. This shows that both the intensity and abundance of the parasite peak in winter, with the lowest levels observed in summer. (Fig.84).

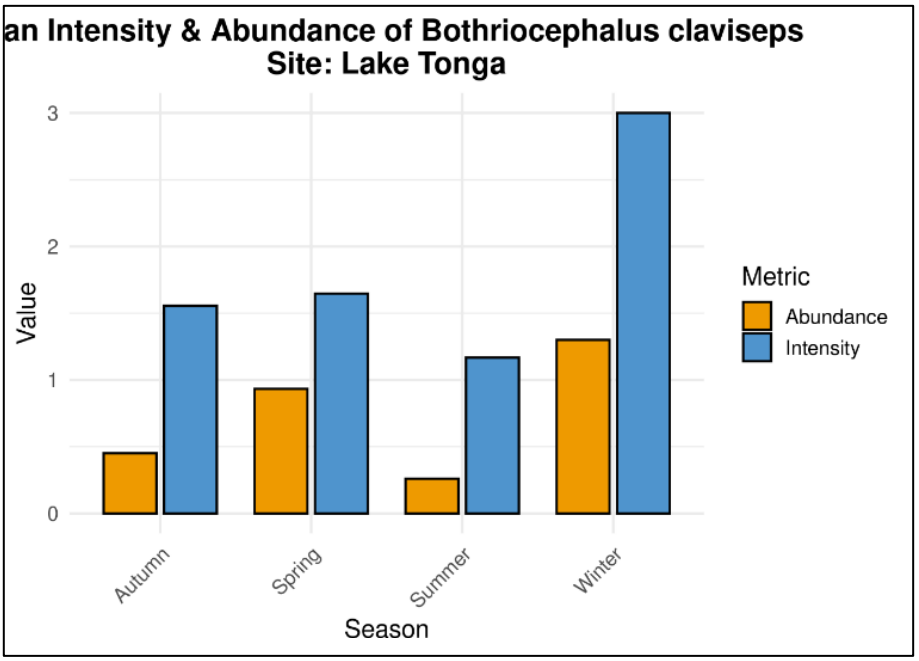

Figure 84: Seasonal Intensity and Abundance of *Bothriocephalus claviseps* in Lake Tonga

4.2.5. Seasonal distribution of parasitological indices of *Bothriocephalus Claviceps* in Wadi El Kebir Jijel:

❖ **Prevalence:**

The prevalence of *Bothriocephalus claviceps* at the Wadi El-Kebir site exhibited pronounced seasonal variation. It was relatively low in autumn (≈28%), increased sharply during spring (≈72%), and subsequently declined to its lowest level in winter (≈18%). These results indicate that parasite prevalence reached its maximum in spring, while winter represented the period of minimal occurrence. (Fig.85).

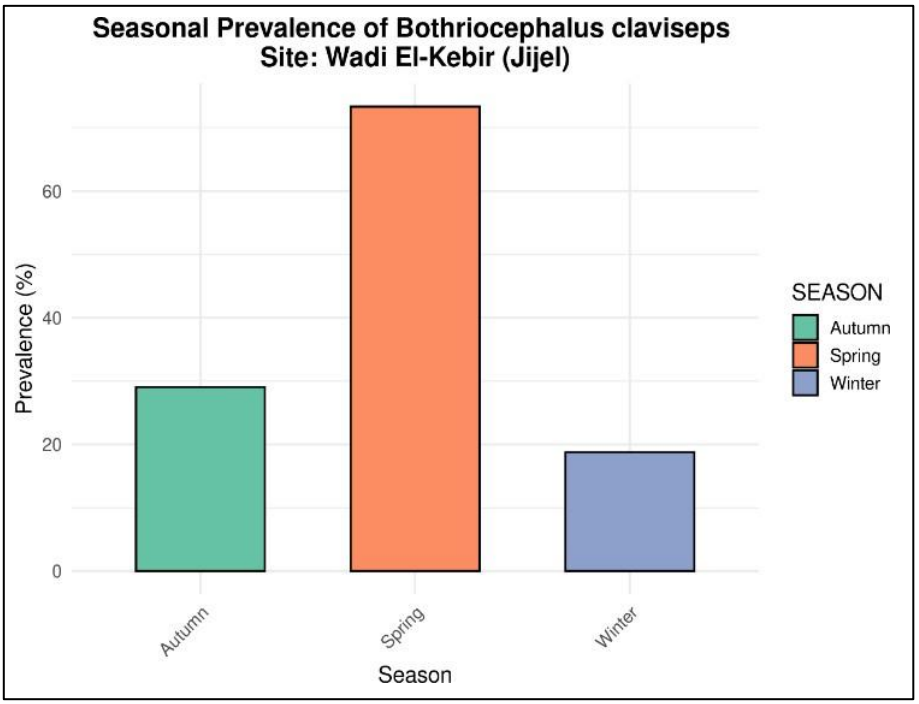

Figure 85: Seasonal prevalence of *Borteriocehalus claviseps* in Wadi El Kebir Jijel.

❖ **Mean intensity and abundance:**

The analysis of *Bothriocephalus claviceps* at the Wadi El-Kebir site demonstrated clear seasonal variability. Mean abundance was lowest in autumn (0.5), increased markedly in spring (1.4), and declined again during winter (0.9). Conversely, mean intensity exhibited a steady rise from autumn (1.6) to spring (1.9), attaining its highest level in winter (4.6). (Fig.86).

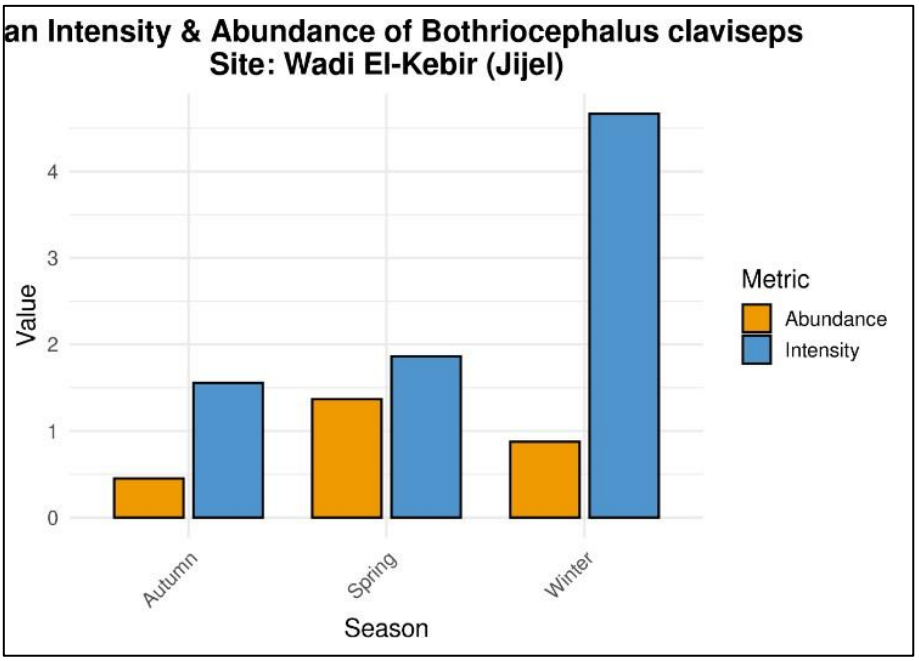

Figure 86: mean intensity and abundance of *Borteriocehalus claviseps* in Wadi El Kebir, Jijel.

4.2.6. Distribution of parasitological indices of *Bothriocephalus claviceps* according to host length classes:

❖ **Prevalence:**

In Lake Tonga eels, the prevalence of *Bothriocephalus claviceps* varied significantly by size class. In the 300–400 mm class, the prevalence was almost 60%; in the 400–500 mm class, it decreased to about 30%; and in the 500–600 mm class, it rose to 43%. Prevalence increased significantly with bigger fish, reaching around 80% in the 600–700 mm class and 100% in the 700–800 mm class. These results show a clear length-related trend, with parasite frequency peaking in the biggest length group and gradually rising with host body length. (Fig.87).

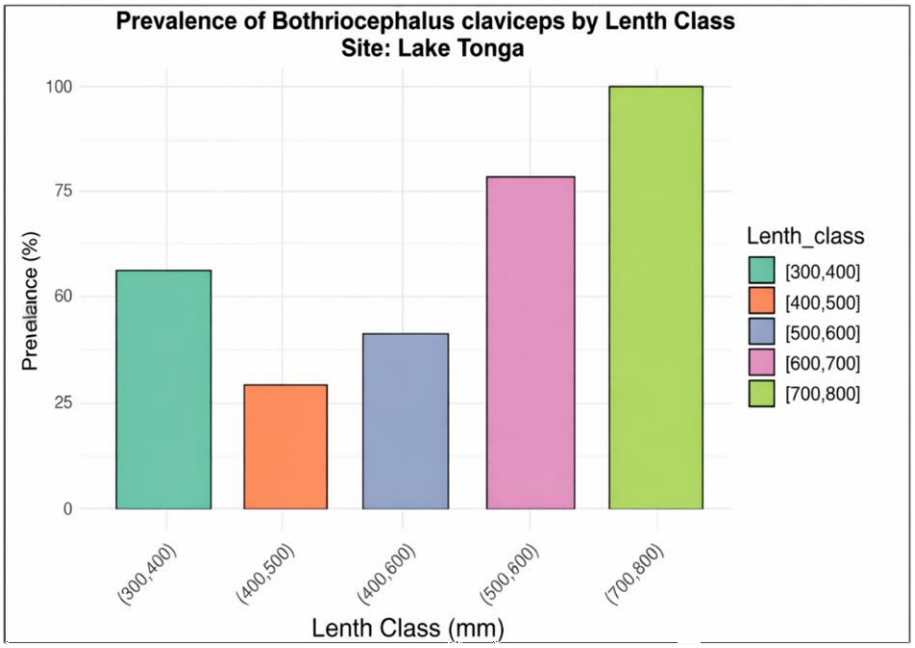

Figure 87: Seasonal prevalence of *Bothriocephalus claviceps* in Lake Tonga.

❖ **Mean intensity and abundance:**

The highest mean intensity of *Bothriocephalus claviceps* was recorded in winter (3.0), representing more than twice the values observed during other seasons. Winter also exhibited the greatest mean abundance (1.4), indicating that both the number of parasites per infected host and the overall parasite burden in the population reached their peak during this period. By contrast, summer presented the lowest values, with a mean abundance of 0.25 and a relatively low intensity of 1.2, reflecting reduced parasite occurrence and load. Autumn and spring exhibited intermediate values, with the mean intensity consistently exceeding the mean abundance.(Fig.88).

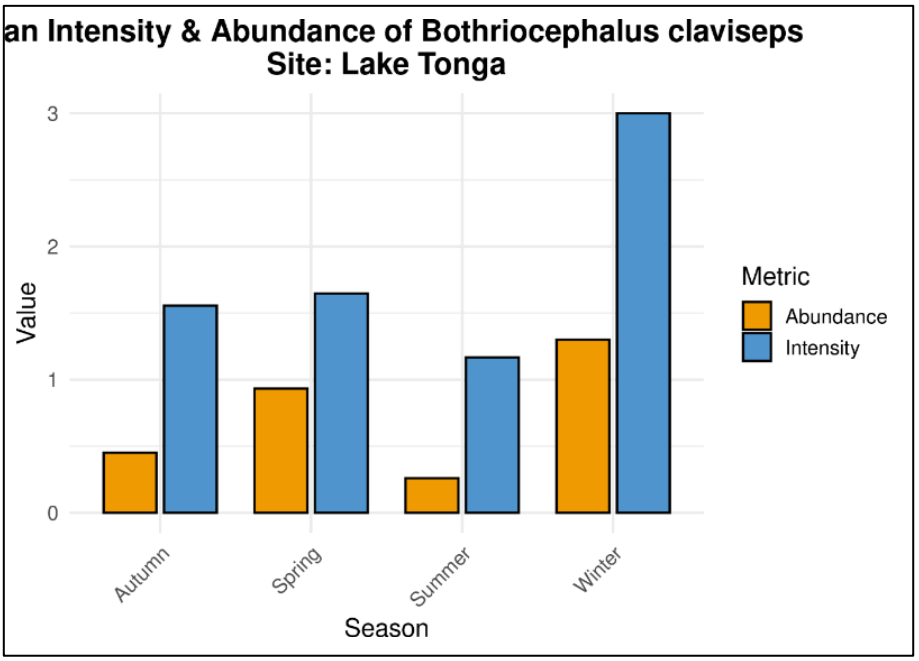

Figure 88: Mean intensity and abundance of *Bothriocephalus claviceps* in Lake Tonga.

❖ **The prevalence:**

The prevalence of *Bothriocephalus claviseps* by length class at Wadi El-Kebir (Jijel) shows clear variation across different length groups. In individuals lengthed between 200 and 300 mm, prevalence is 100%, meaning all individuals in this class are infected. This is also true for the largest length class, 600 to 700 mm, also with 100% prevalence. For the intermediate length class of 500 to 600 mm, about 60% of individuals are infected. The 400 to 500 mm length class has a prevalence of approximately 35%, and the 300 to 400 mm length class has the lowest prevalence at around 12%. This indicates that *Bothriocephalus claviseps* infection is most widespread in the smallest and largest length classes at this site, with lower prevalence in the intermediate length classes. (Fig.89).

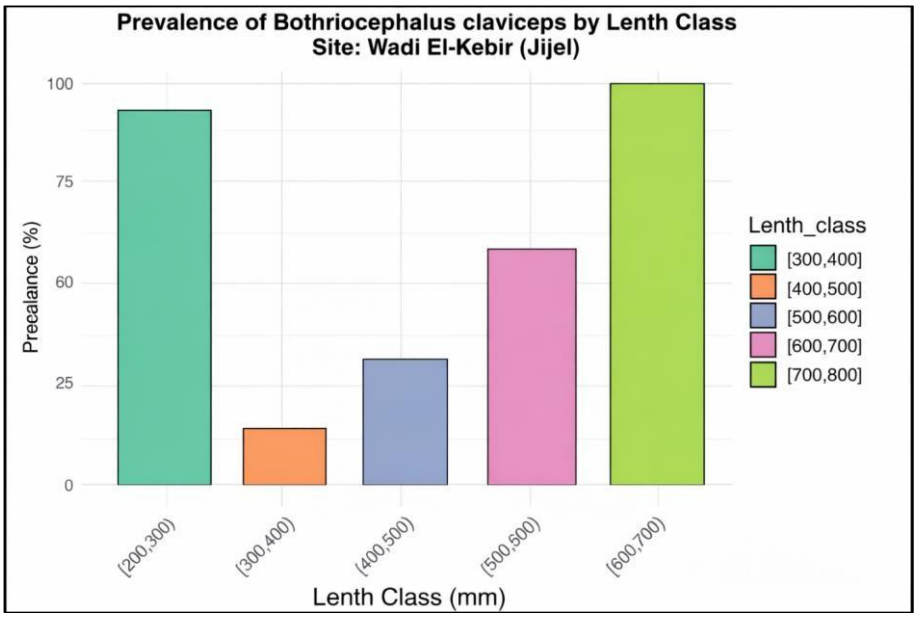

Figure 89: Prevalence of *Bothriocephalus claviseps* by length class at Wadi El-Kebir (Jijel).

- **Mean intensity and abundance:**

At the Wadi El-Kebir site, the highest parasite intensity of *Bothriocephalus claviceps* was observed in winter (4.7), markedly exceeding values recorded in other seasons and indicating a greater number of parasites per infected host during this period. Spring exhibited the second highest intensity (≈1.85), followed by autumn (≈1.55). With respect to abundance, the highest value was recorded in spring (1.35), while winter and autumn showed lower levels (0.90 and 0.45, respectively). (Fig.90)

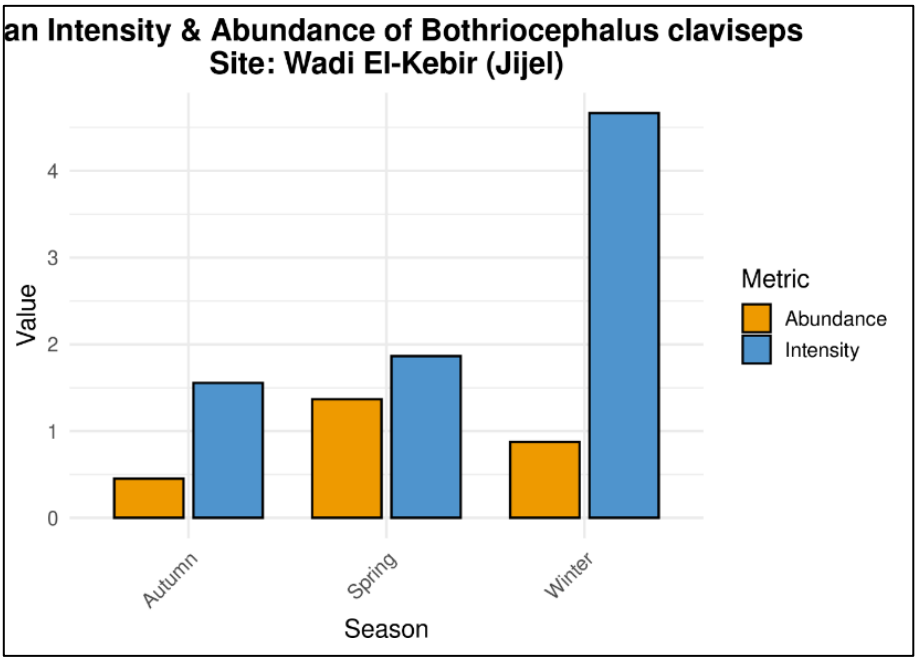

Figure 90: Mean intensity and abundance of *Bothriocephalus claviseps* by length class at Wadi El-Kebir (Jijel).

4.2.7. Seasonal Distribution of Parasitological Indices of *Anguillicoloides crassus* in Lake Tonga:

❖ **Prevalence:**

The seasonal prevalence of *Anguillicoloides crassus* in European eels from Lake Tonga demonstrated marked temporal variation. The highest prevalence was recorded during winter (≈approximately 68%), indicating this season as the peak period for infection. Spring exhibited a slightly lower prevalence (≈approximately 60%), while autumn showed intermediate levels (≈approximately 57%). In contrast, summer was characterized by the lowest prevalence (≈48%), suggesting a seasonal decline in parasite occurrence during warmer months. Overall, the difference between the maximum (winter) and minimum (summer) prevalence was approximately 20%. (Fig.91).

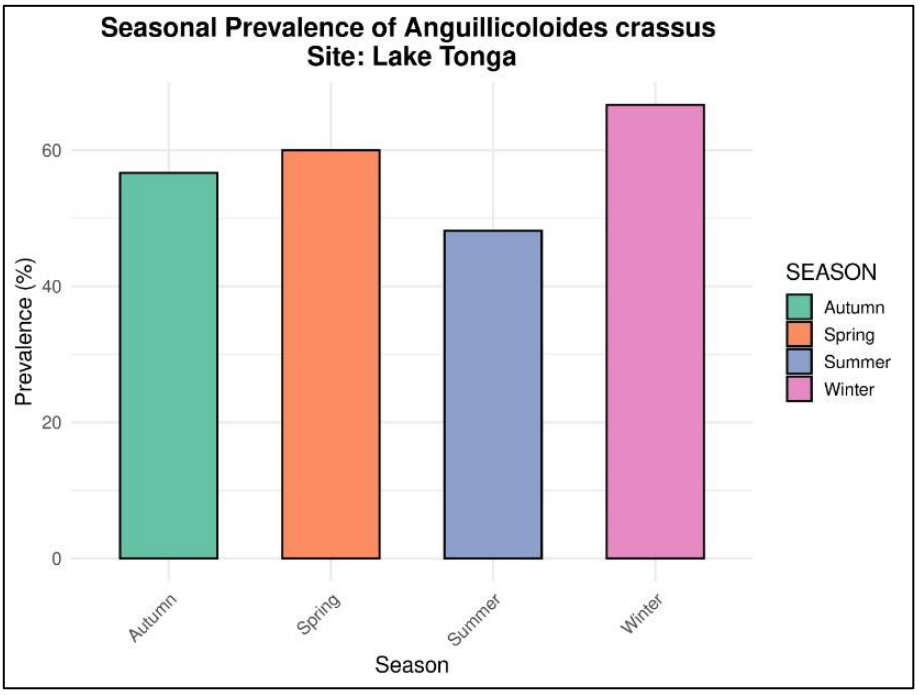

Figure 91: Seasonal prevalence of *Anguillicoloides crassus* in Lake Tonga.

❖ **Mean intensity and abundance:**

The analysis of mean intensity and abundance of *Anguillicoloides crassus* in eels from Lake Tonga revealed pronounced seasonal variation, with winter emerging as the peak period of infection. Mean intensity reached its maximum in winter (≈4.9 parasites per infected eel), followed by summer (≈3.8), spring (≈2.8), and autumn (≈2.3), representing more than a twofold increase from autumn to winter. A similar trend was observed for mean abundance, which was highest in winter (≈3.3 parasites per examined eel), moderate in summer (≈1.8), and lowest in spring (≈1.7) and autumn (≈1.3). (Fig.92).

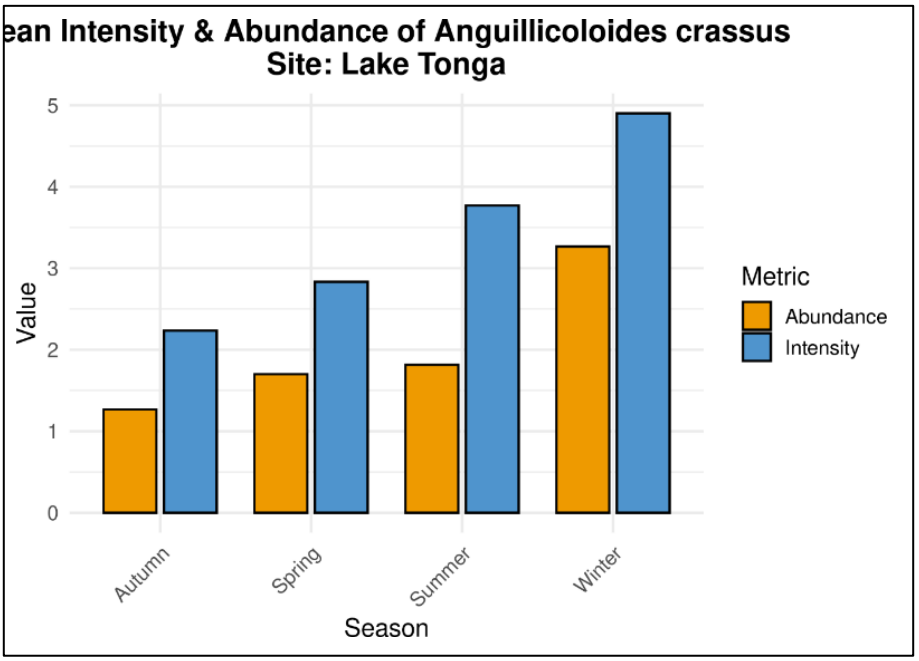

Figure 92: Mean intensity and abundance of *Anguillicoloides crassus* in Lake Tonga.

4.2.8. Seasonal Distribution of Parasitological Indices of *Anguillicoloides crassus* in Wadi El-Kebir:

❖ **Prevalence:**

The prevalence of *Anguillicoloides crassus* in eels from Wadi El-Kebir (Jijel) exhibited relatively stable yet seasonally structured patterns. Winter showed the highest prevalence (≈67%), followed by spring (≈60%), while autumn recorded the lowest value (≈58%). The overall variation across seasons was limited (≈9 percentage points), indicating a consistently high level of infection, with rates exceeding 55% in all cases.(Fig.93).

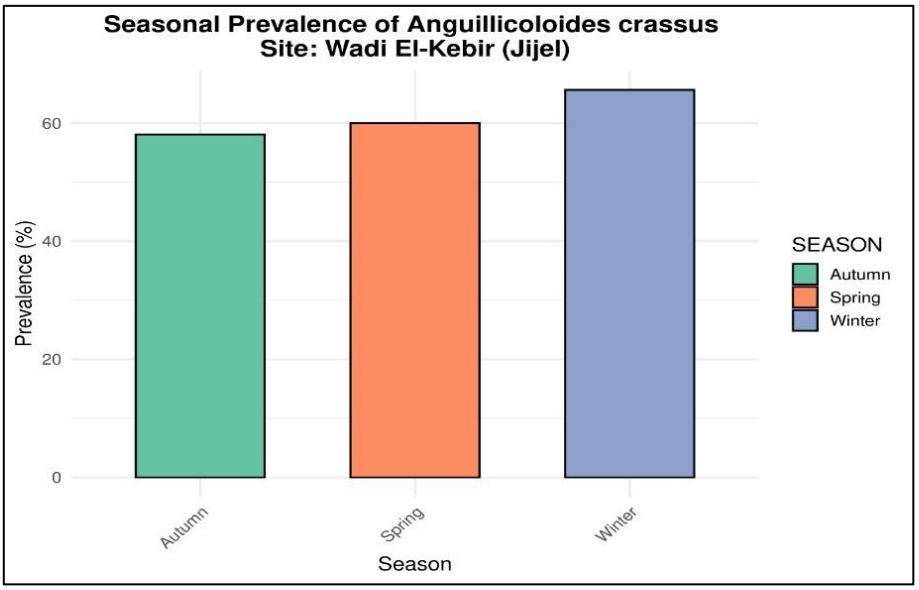

Figure 93: Seasonal prevalence of *Anguillicoloides crassus* in Wadi El-Kebir Jijel.

❖ **Mean intensity and abundance:**

The infection dynamics of *Anguillicoloides crassus* in Wadi El-Kebir showed clear seasonal variation, peaking in winter with mean intensity (5.5) and abundance (3.7), far exceeding values in autumn (2.2; 1.3) and spring (1.8; 1.1). (Fig.94).

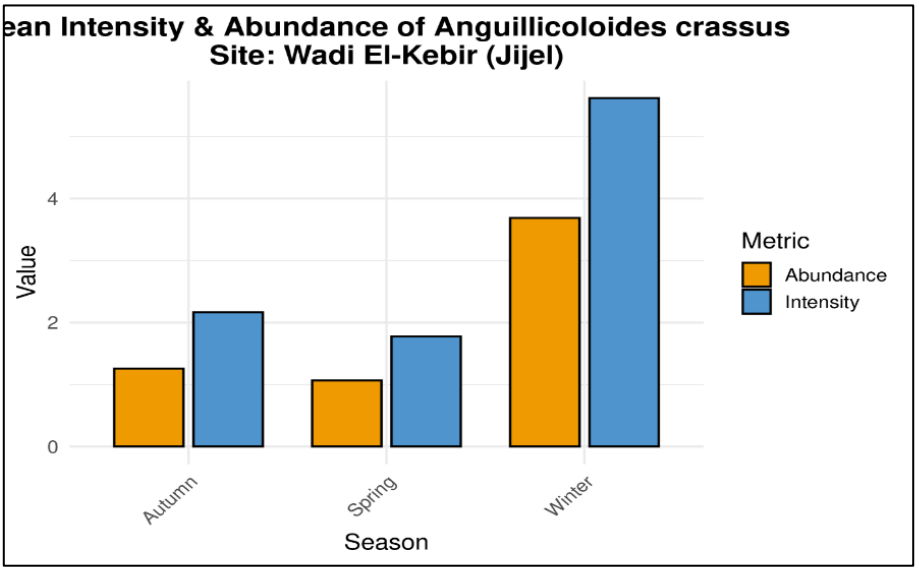

Figure 94: mean intensity and abundance of *Anguillicoloides crassus* in Wadi El-Kebir Jijel.

4.2.9. Distribution of the parasitological indices of *Anguillicoloides crassus* according to length classes in Lake Tonga:

❖ **Prevalence:**

The prevalence of *Anguillicoloides crassus* at Lake Tonga exhibited a strong positive correlation with eel length class. The smallest eels (300-400 mm) showed the lowest infection rate at approximately 17%, increasing progressively through 50% in the 400-500 mm class and 73% in the 500-600 mm class. The two largest length classes (600-700 mm and 700-800 mm) both demonstrated complete or near-complete infection at 100% prevalence. This represents a nearly sixfold increase from the smallest to largest length classes, suggesting that larger eels experience greater cumulative exposure to the parasite over time or that infection persists and accumulates with age, with eels exceeding 600 mm being almost invariably infected. (Fig.95).

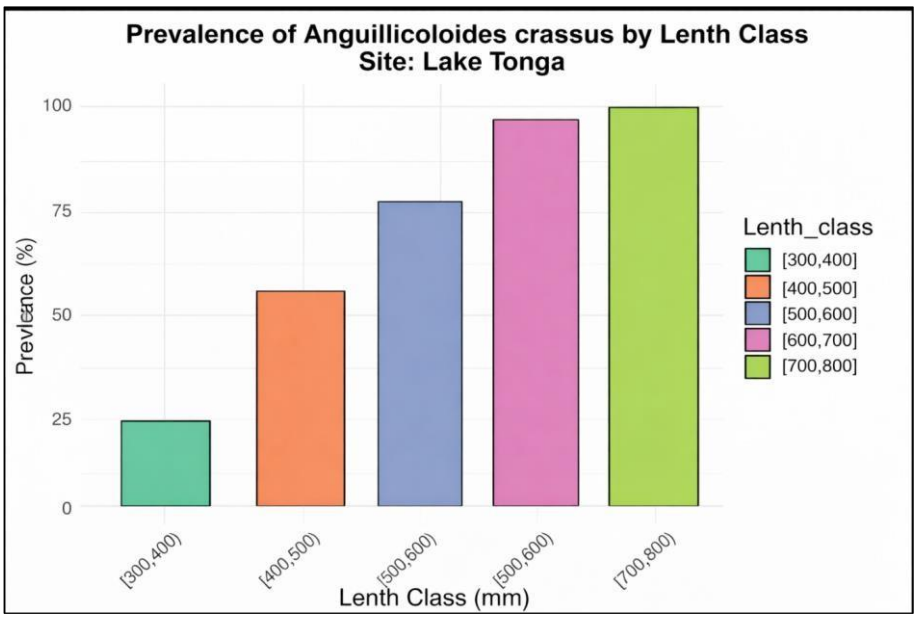

Figure 95: Prevalence of *Anguillicoloides crassus* at Lake Tonga by size classes.

❖ **Mean intensity and abundance:**

At Lake Tonga, the mean intensity and abundance of *Anguillicoloides crassus* showed a clear positive association with eel length class. Mean intensity rose from 2.0 parasites per infected eel in the 300–400 mm class to 6.0 in the 700–800 mm class, with intermediate values of 2.8, 4.3, and 3.5 for the 400–500 mm, 500–600 mm, and 600–700 mm classes, respectively. Mean abundance followed a similar pattern, increasing from 0.3 in the smallest class to 6.0 in the largest, with intermediate values of 1.4, 3.2, and 3.5. (Fig.96).

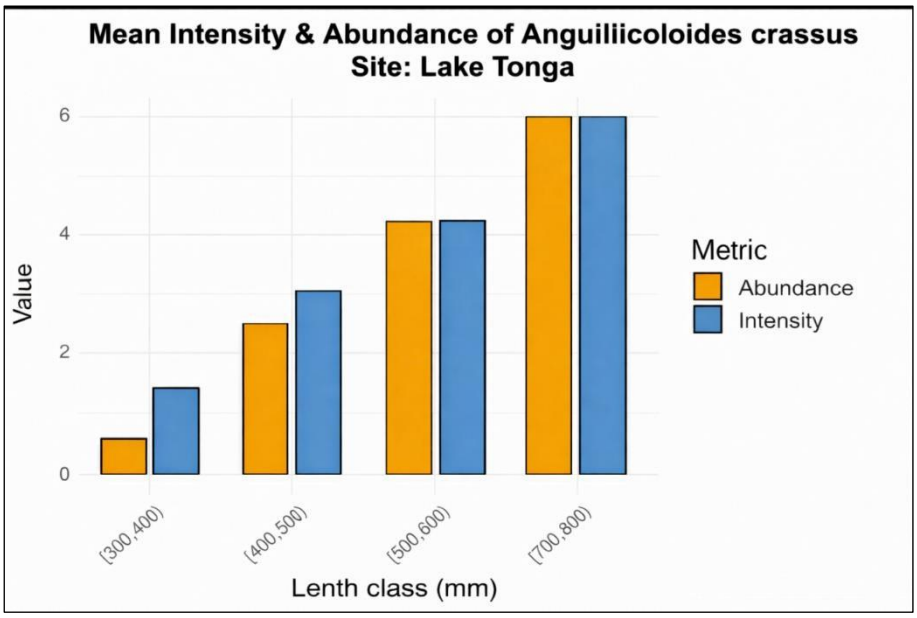

Figure 96: Mean intensity and abundance of *Anguillicoloides crassus* at Lake Tonga.

❖ **Prevalence:**

The prevalence of *Anguillicoloides crassus* at Wadi El-Kebir displayed a distinct non-linear relationship with eel length class. The smallest (200-300 mm) and largest (600-700 mm) length classes both exhibited complete infection at 100% prevalence, while intermediate length classes showed considerably lower infection rates. Eels in the 300-400 mm class demonstrated approximately 70% prevalence, the 500-600 mm class showed roughly 70% prevalence, and the 400-500 mm class exhibited the lowest infection rate at approximately 44%. (Fig.97).

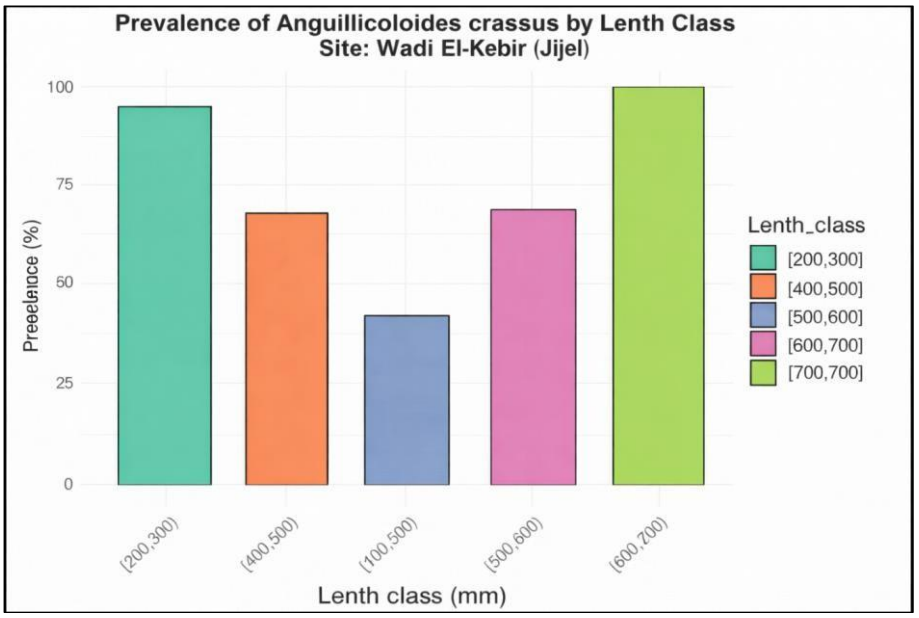

Figure 97: Prevalence of *Anguillicoloides crassus* at Wadi El-Kebir by length classes.

❖ **Mea intensity and abundance:**

At Wadi El-Kebir, *Anguillicoloides crassus* infection showed a bimodal length -related pattern. Mean intensity peaked at 6.0 parasites per eel in the 300–400 mm class, dropped to 1.9 in the 400–500 mm class, then rose slightly to 2.5–2.4 in larger classes, with the 200–300 mm class showing 4.0. Mean abundance followed a similar trend, with high values in smaller eels (4.2 and 4.0), a decline in mid- length eels (0.8), and recovery in larger ones (1.7–2.4). (Fig.98).

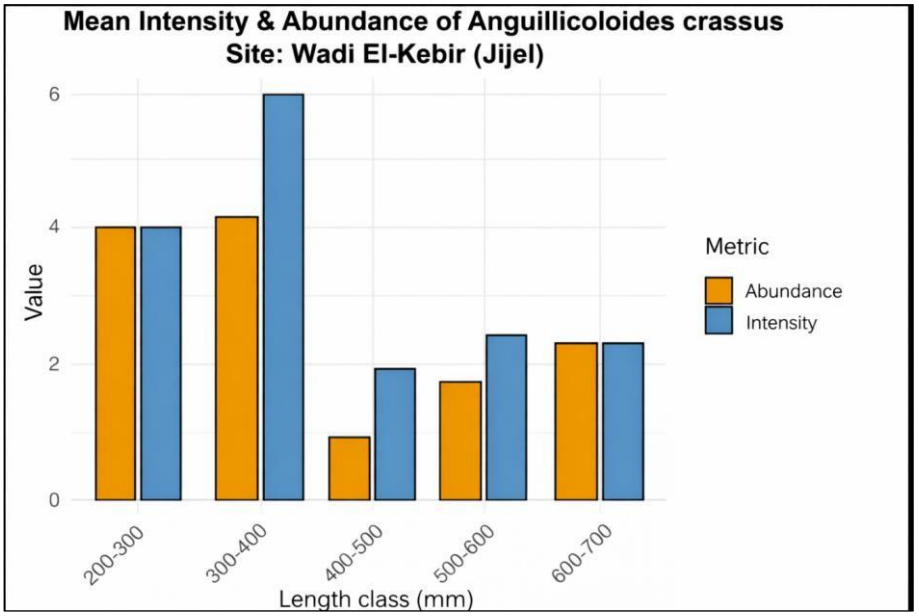

Figure 98: Mean intensity and abundance of *Anguillicoloides crassus* at Wadi El-Kebir by length classes.

4.2.10. Seasonal Distribution of the parasitological indices of *Pseudodactylogyrus sp.*in Lake Tonga:

❖ **Prevalence:**

The seasonal prevalence of *Pseudodactylogyrus* sp. in eels from Lake Tonga exhibited pronounced temporal fluctuations throughout the year. Winter showed the highest infection rate, reaching approximately 80%, followed by autumn at around 71% and spring at roughly 64%. Summer recorded the lowest prevalence (≈40%), representing a twofold reduction compared to the winter peak. (Fig.99).

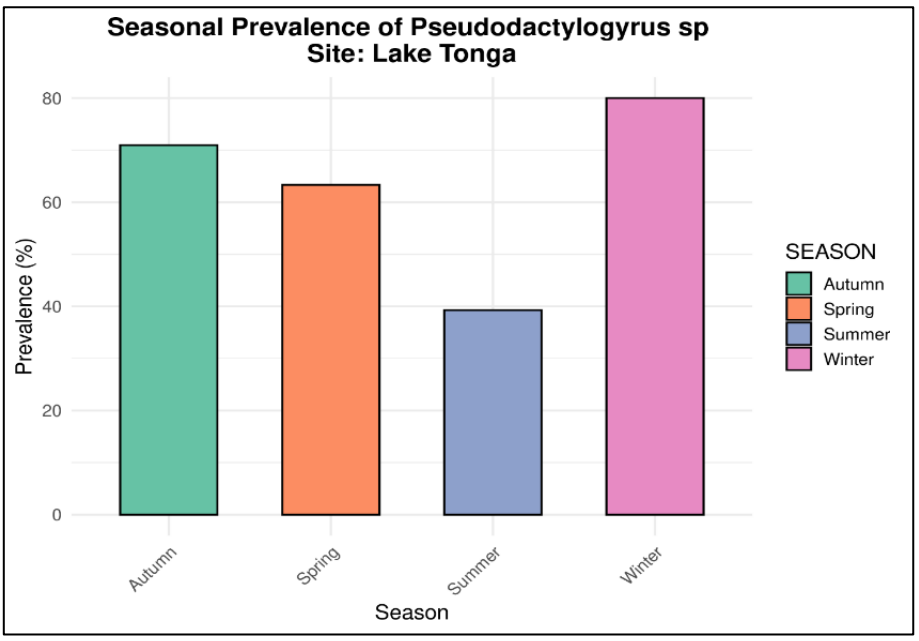

Figure 99: seasonal prevalence of *Pseudodactylogyrus sp*. in eels from Lake Tonga

❖ **Mean intensity and abundance:**

Seasonal variations were observed in the mean intensity and total amount of *Pseudodactylogyrus* sp. in Lake Tonga. Summer had the greatest mean intensity (≈5.0 parasites per infected eel), winter (≈3.3), autumn (≈4.0), and spring (≈3.4). The trend in mean abundance was similar but less pronounced, peaking in fall (≈2.9), followed by winter (≈2.6), spring (≈2.1), and summer (≈1.9). (Fig.100).

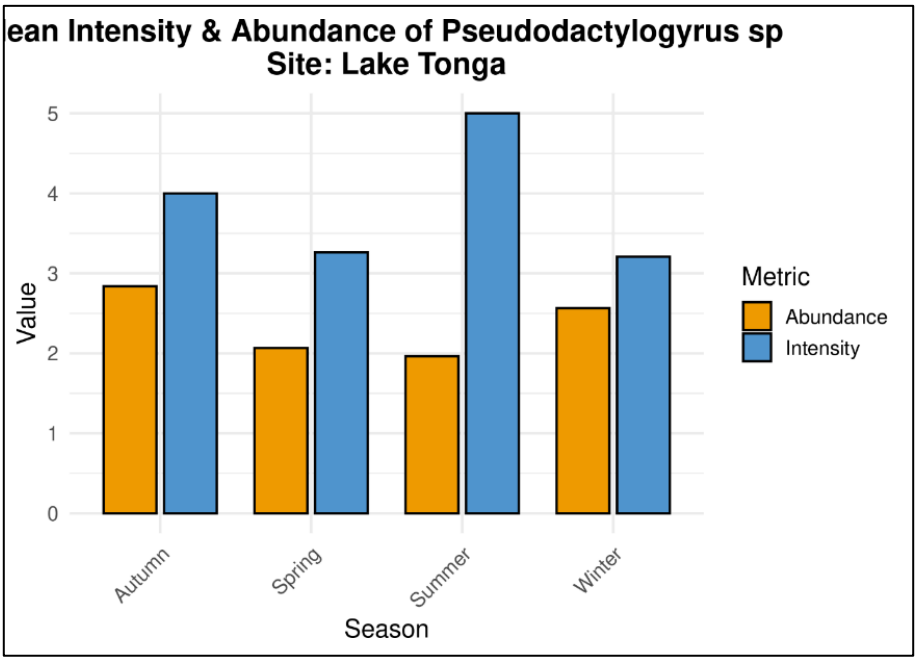

Figure 100: Seasonal variation of the mean intensity and abundance of *Pseudodactylogyrus sp*. in Lake Tonga.

4.2.11. Seasonal Distribution of the parasitological indices of *Pseudodactylogyrus sp in* Wadi El-Kebir, Jijel:

❖ **Prevalence:**

The seasonal prevalence of *Pseudodactylogyrus* sp. at Wadi El-Kebir exhibited notable variation across three seasons sampled. Autumn and winter both recorded similarly high infection rates at approximately 73% and 71% respectively, while spring showed a considerably lower prevalence at around 50%. This represents a difference of approximately 23 percentage points between the highest (autumn) and lowest (spring) infection rates. (Fig.101).

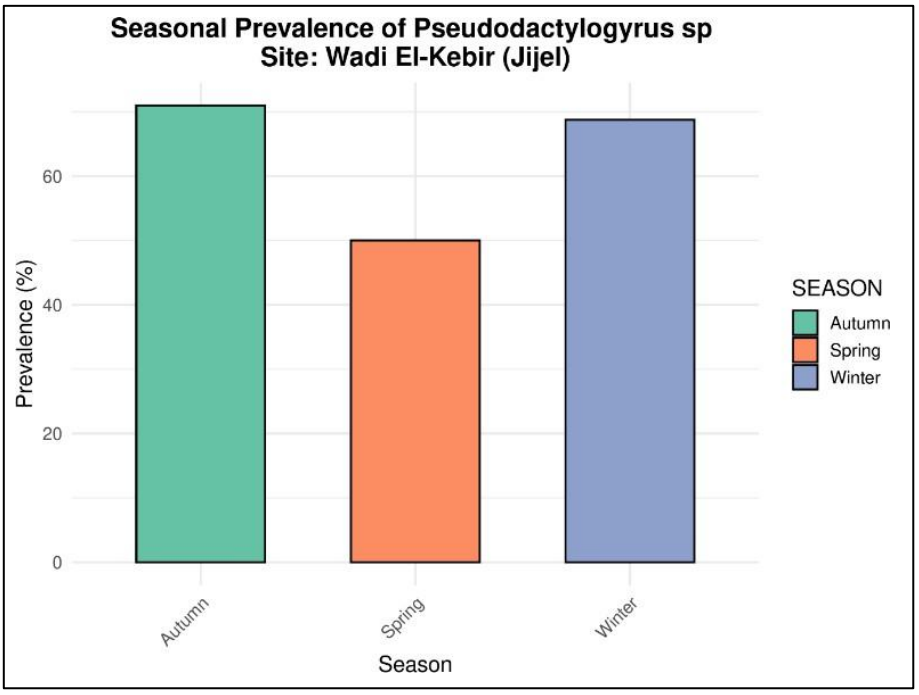

Figure 101: Seasonal prevalence of *Pseudodactylogyrus sp*. at Wadi El-Kebir.

❖ **Mean intensity and abundance:**

The mean intensity and abundance of *Pseudodactylogyrus* sp. at Wadi El-Kebir exhibited marked seasonal variation. Mean intensity was highest during autumn at approximately 4.0 parasites per infected eel, followed by winter at 3.8, while spring showed considerably lower values at 1.7. Mean abundance displayed a similar seasonal pattern, reaching approximately 2.8 parasites per examined eel in both autumn and winter, substantially higher than the spring value of 0.9. (Fig.102).

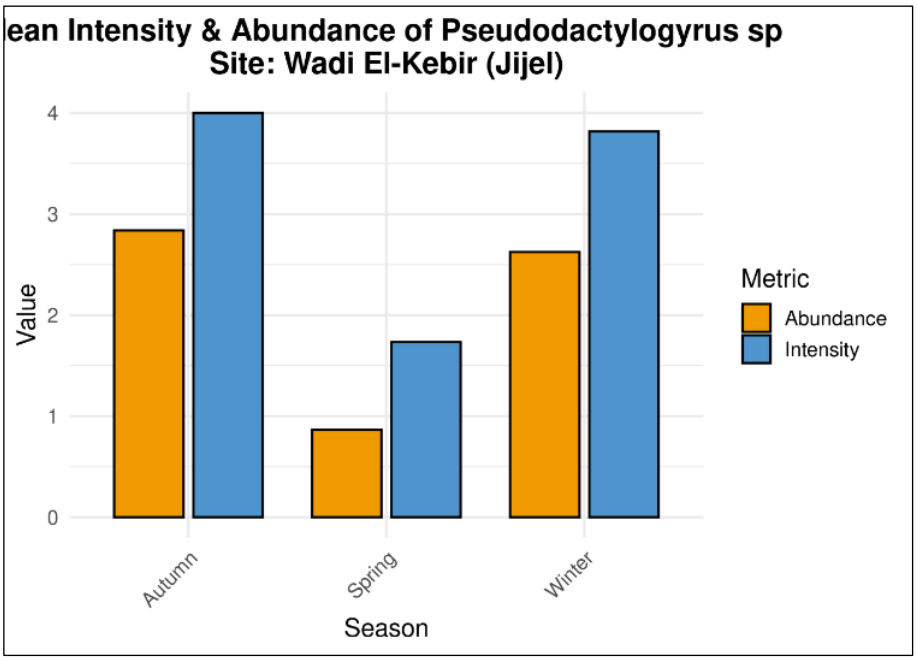

Figure 102: Seasonal mean intensity and abundance of *Pseudodactylogyrus sp.* at Wadi El-Kebir

4.2.12. Distribution of the parasitological indices of *Pseudodactylogyrus* ***sp.*** in Lake Tonga according to length classes:

❖ **Prevalence:**

At Lake Tonga, the eel length class showed a significant correlation with the occurrence of *Pseudodactylogyrus* sp. The lowest infection incidence, at 17%, was seen in the smallest eels (300–400 mm), which increased gradually to 63% in the 400–500 mm class, 68% in the 500–600 mm class, and 80% in the 600–700 mm class. At 100% incidence, the highest length class (700-800 mm) attained full infection saturation. (Fig.103).

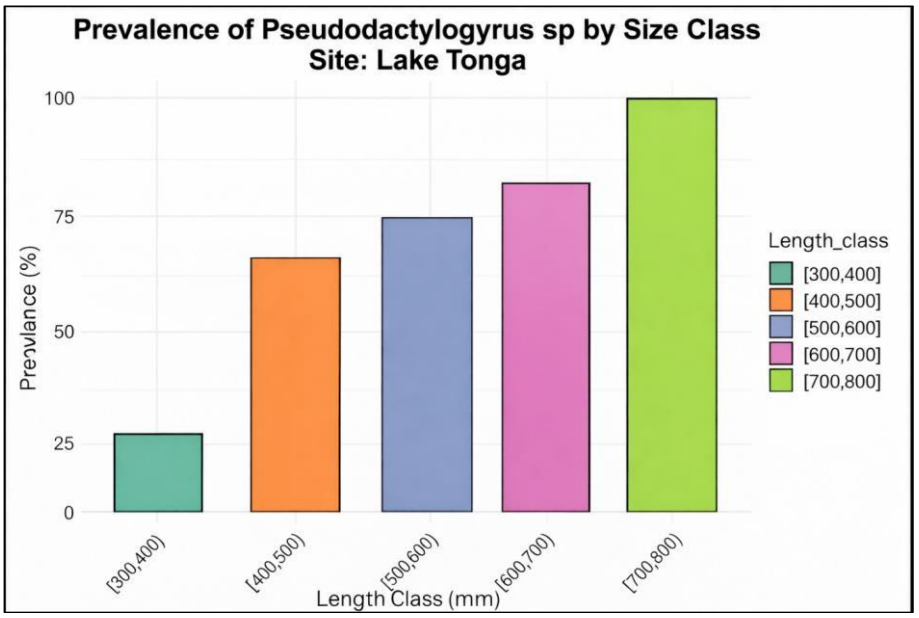

Figure 103: Prevalence of *Pseudodactylogyrus sp*. at Lake Tonga by length classes.

❖ **Mean intensity and abundance:**

There were also noticeable length -dependent differences in the mean intensity and abundance of *Pseudodactylogyrus sp*. in Lake Tonga eels. The lowest length class (300–400 mm) had the highest mean intensity, with an average of almost 13.5 parasites per infected eel. In the next size classes (400–700 mm), it then dropped precipitously to very steady levels of around 3.5 parasites, before rising somewhat to 7.0 parasites in the greatest size class (700–800 mm). The mean abundance, on the other hand, increased gradually with host length, from about 2.2 parasites per studied eel in the 300–400 mm class to 7.0 in the 700–800 mm class, with mid-sized eels showing intermediate values of 2.0, 2.3, and 2.7. (Fig.104).

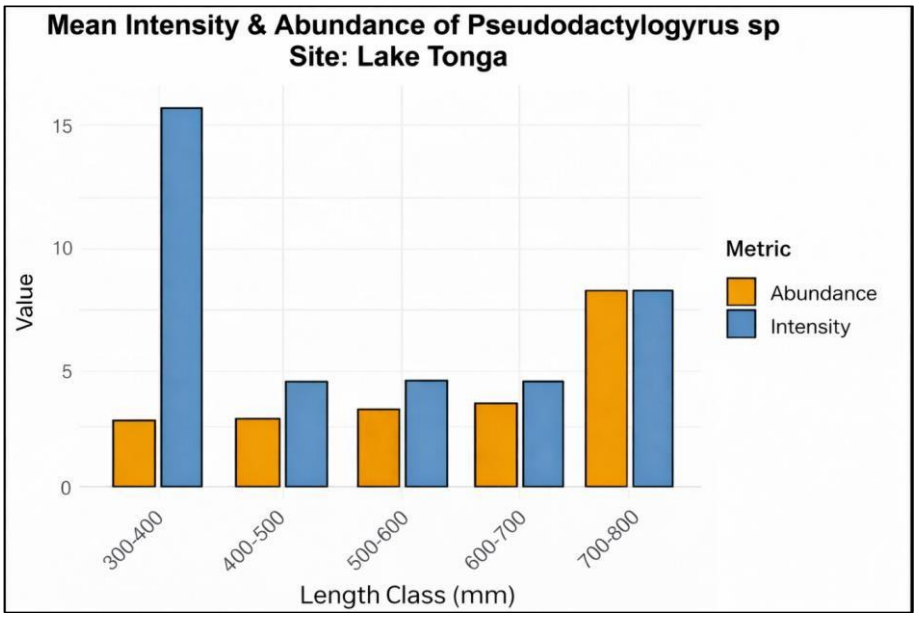

Figure 104: Mean intensity and abundance of *Pseudodactylogyrus* sp. in Lake Tonga eels by length classes.

❖ **Prevalence:**

At Wadi El-Kebir, the prevalence of *Pseudodactylogyrus* sp. varied significantly with eel length class, ranging from 52% to 100%. Infection rates dropped significantly to almost 52% in the 300–400 mm class, whereas the maximum incidence (100%) was seen in the smallest eels (200–300 mm). The prevalence then slightly decreased to around 64% in the 600–700 mm category after increasing somewhat in the 400–500 mm (≈66%) and 500–600 mm (≈69%) classes. (Fig.105).

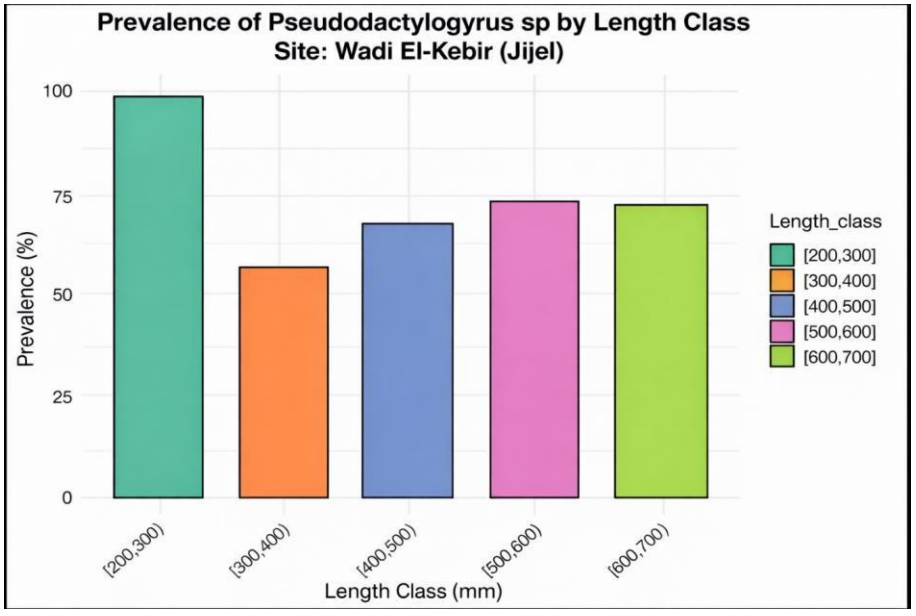

Figure 105: The prevalence of *Pseudodactylogyrus* sp. at Wadi El-Kebir, by length classes.

❖ **Mean intensity and abundance:**

At Wadi El-Kebir, *Pseudodactylogyrus* sp. abundance and mean intensity varied by eel length class, with the 400–500 mm group showing the highest abundance. The mean intensity of this class was approximately 4.3 parasites per infected eel, whereas the 300–400 mm and 500–600 mm classes had mean values of 2.9 and 2.8, respectively. The smallest (200–300 mm) and biggest (600–700 mm) eels had the lowest levels (≈2.0). In the 400–500 mm class, the mean abundance peaked at 2.7 parasites per analyzed eel, whereas in other size groups, the values ranged from 1.3 to 2.0. (Fig.106).

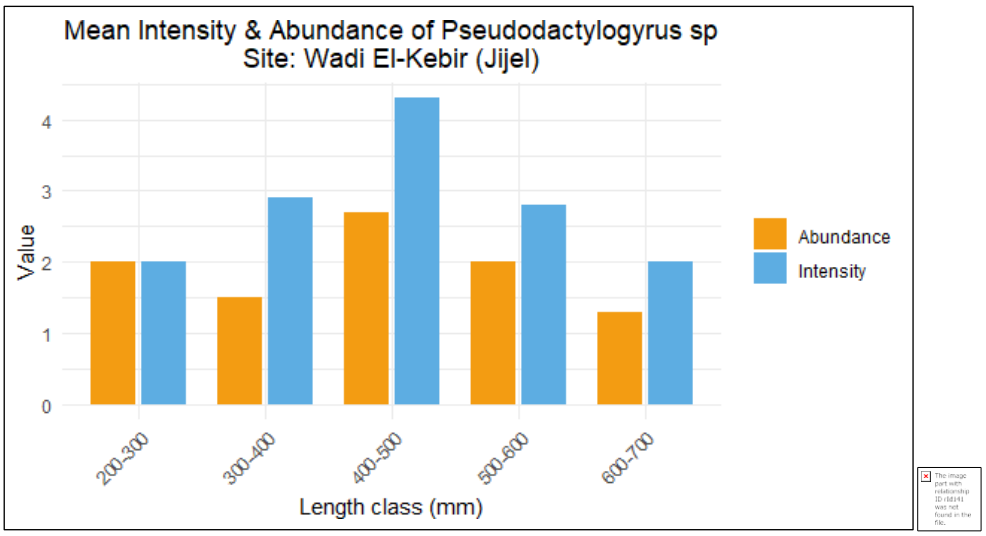

Figure 106: Mean intensity and abundance of *Pseudodactylogyrus* sp. at Wadi El-Kebir.

4.2.13. Seasonal Distribution of the parasitological indices of *Ergasilus gibbus* in Lake Tonga:

❖ **Prevalence:**

Prevalence of *E. gibbus* at Lake Tonga displayed pronounced seasonal variation, peaking during winter (≈77%), when environmental conditions appear most favorable for infection or parasite reproduction. Autumn recorded the second-highest prevalence (≈52%), indicating that parasite activity remains substantial as temperatures decline. In contrast, prevalence dropped sharply in spring (≈27%) and reached a minimum in summer (≈4%), when infections were nearly absent.(Fig.107).

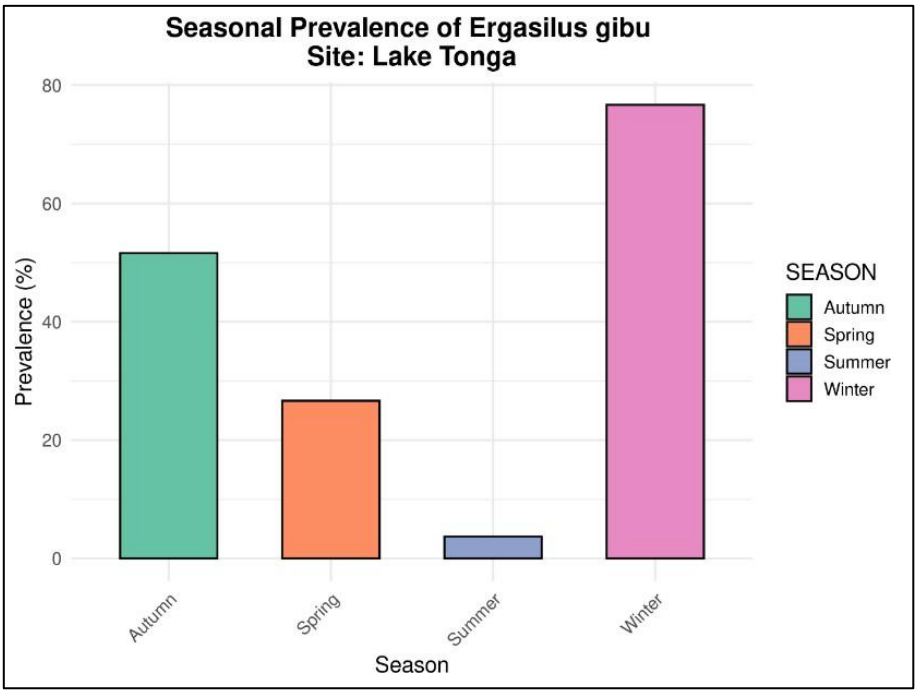

Figure 107: Seasonal prevalence variation of *Ergasilus gibbus* in Lake Tonga.

❖ **Mean intensity and abundance:**

Ergasilus gibbus abundance and mean intensity in Lake Tonga showed significant seasonal fluctuation. Winter had the greatest values (intensity ≈2.52; abundance ≈1.95; prevalence 77%), suggesting that the coldest months had the highest levels of infection and parasite buildup. Summer (intensity ≈1.00; abundance ≈0.05; prevalence 4%), followed by autumn (intensity ≈1.38; abundance ≈0.72; prevalence 52%) and spring (intensity ≈1.88; abundance ≈0.50; prevalence 27%), had the lowest levels of infection. (Fig.108).

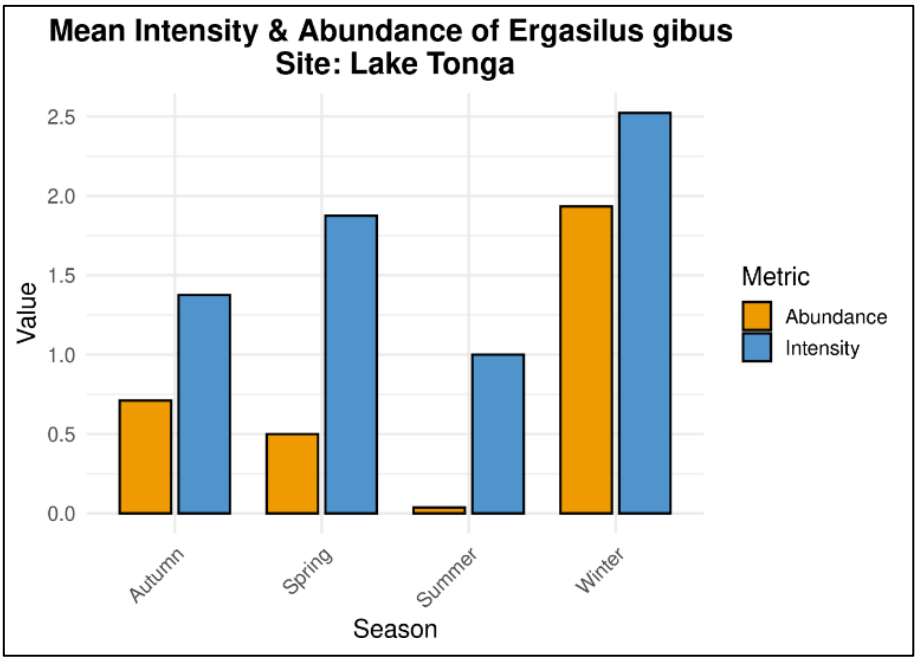

Figure 108: Seasonal variation of the abundance and mean intensity of *Ergasilus gibbus* in Lake Tonga.

4.2.14. Seasonal Distribution of the parasitological indices of *Ergasilus gibbus* in Wadi El-Kebir :

❖ **Prevalence:**

At Wadi El-Kebir, *E. gibbus* prevalence exhibited strong seasonal variation across the three sampled periods. The highest infection rate occurred in spring (≈75%), followed by winter (≈63%), and autumn (≈52%). (Fig.109).

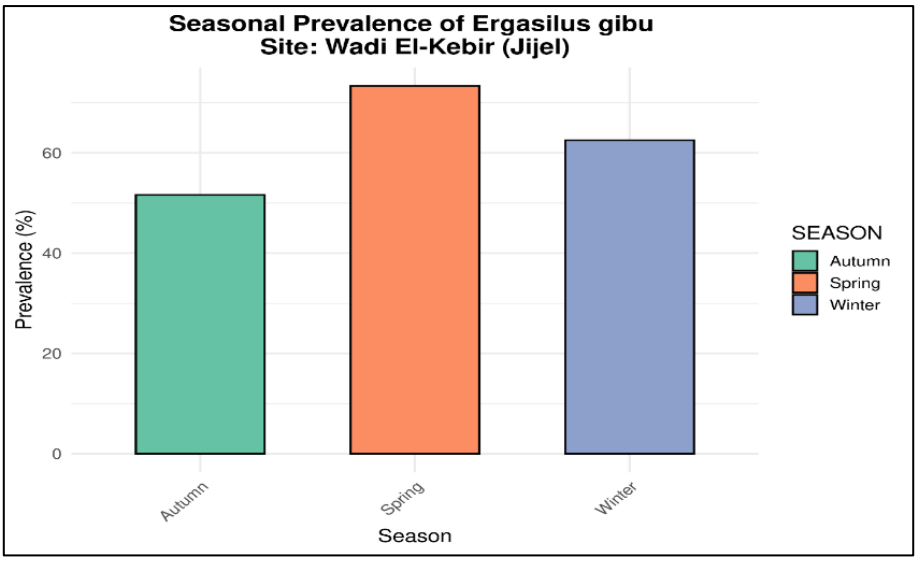

Figure 109: Seasonal variation of the prevalence of *E. gibbus*: At Wadi El-Kebir.

❖ **Mean intensity and abundance:**

With an abundance of 1.31 and an intensity of 2.08, winter at Wadi El-Kebir has the highest parasite load, meaning that infected fish carry over two parasites each despite only a 63% prevalence. Spring, on the other hand, has the highest prevalence (75%) but moderate loads, indicating widespread but lighter infections, while autumn has the lowest values, with an abundance of 0.71 and an intensity of 1.38. (Fig.110).

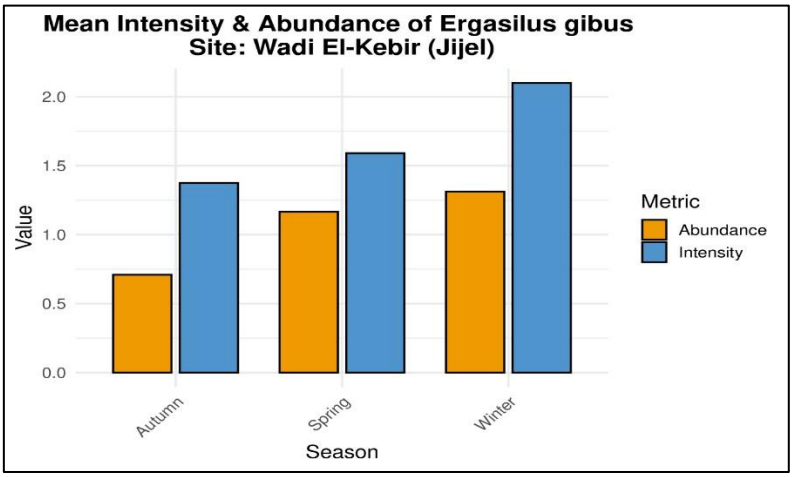

Figure 110: Mean intensity and abundance variation of *E. gibbus* at Wadi El-Kebir.

4.2.15. Distribution of the parasitological indices of *Ergasilus gibbus* in Lake Tonga according to length classes:

❖ **Prevalence:**

At Lake Tonga, parasite prevalence increases dramatically with fish length. The smallest fish (300-400mm) show only 33% prevalence, while medium- length fish (400-500mm and 500-600mm) display similar moderate infection rates of 40% and 35% respectively. Larger fish experience much higher prevalence, with the 600-700mm class reaching 80% and the largest fish (700-800mm) showing complete infection at 100%. (Fig.111).

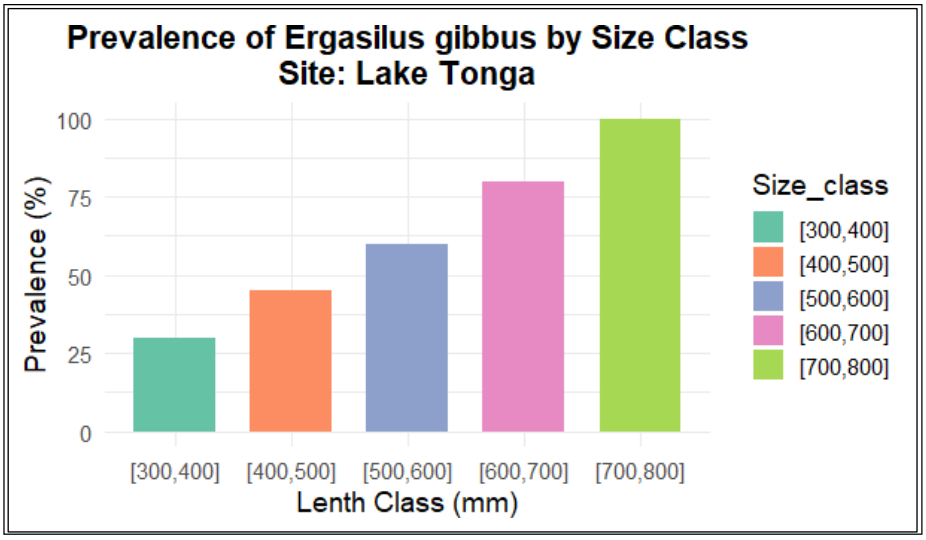

Figure 111: The prevalence variation of *Ergasilus gibbus* by length classes in Lake Tonga.

❖ **Mean intensity and abundance:**

Parasite burden increases sharply with fish size at Lake Tonga. Smaller fish (300-400mm, 400-500mm, and 500-600mm) show consistently low abundance (0.67, 0.75, 0.70) and similar intensity values (2.0, 1.88, 2.0), indicating light infections when they occur. However, the 600-700mm class shows a marked increase with abundance of 2.0 and intensity of 2.5, while the largest fish (700-800mm) display the highest parasite loads with abundance and intensity both reaching 3.0. (Fig.112).

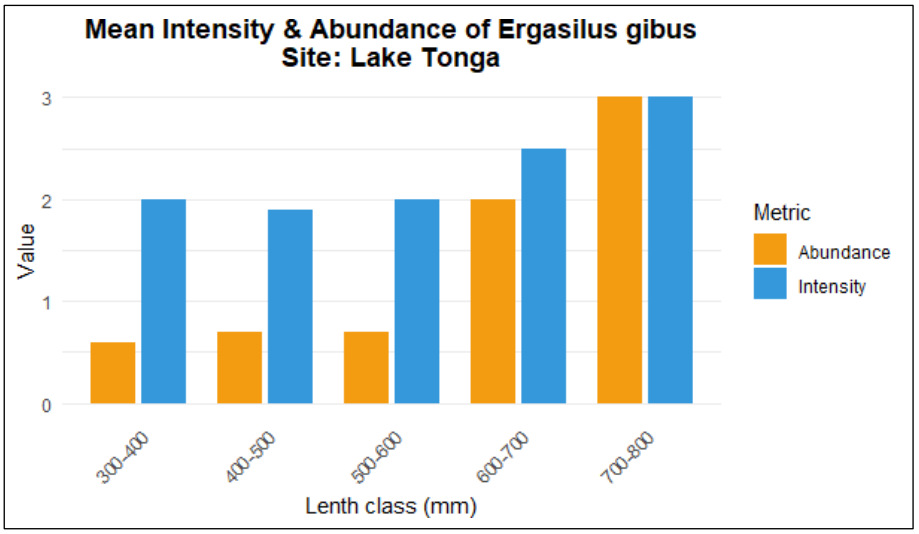

Figure 112: The mean intensity and abundance variation of *Ergasilus gibus* in Lake Tonga by length classes.

4.2.16. Distribution of the parasitological indices of *Ergasilus gibbus* in Wadi el kebir Jijel according to length classes:

❖ **Prevalence:**

At Wadi El-Kebir, parasite prevalence exhibits a bimodal distribution across host length classes. The smallest (200-300mm) and largest (600-700mm) fish both demonstrate 100% infection rates, while intermediate size classes show substantially lower prevalence: 67% (300-400mm), 62% (400-500mm), and 57% (500-600mm). (Fig.113).

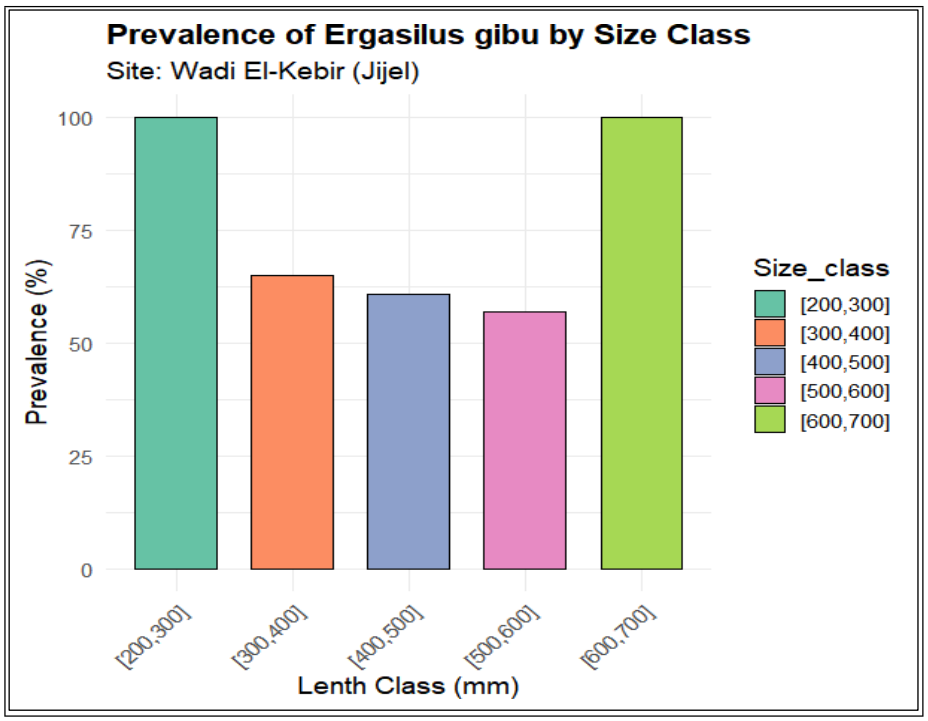

Figure 113: Prevalence variation of the Ergasilus gibus at Wadi El-Kebir by length classes.

❖ **Mean intensity and abundance:**

Parasite load metrics at Wadi El-Kebir demonstrate variable patterns across host length classes. The smallest fish (200-300mm) exhibit equal abundance and intensity values of 1.0, reflecting uniform single-parasite infections consistent with 100% prevalence. The 300-400mm class shows the highest intensity (2.0) with an abundance of 1.33, indicating heavier infections despite moderate prevalence (67%). Mid-lengthed fish (400-500mm and 500-600mm) display intermediate values with abundance of 1.05 and 0.83 and intensity of 1.71 and 1.47 respectively. The largest fish (600-700mm) present abundance of 1.7 and intensity of 1.7, where the convergence of these metrics reflects the 100% prevalence in this length class. (Fig.114).

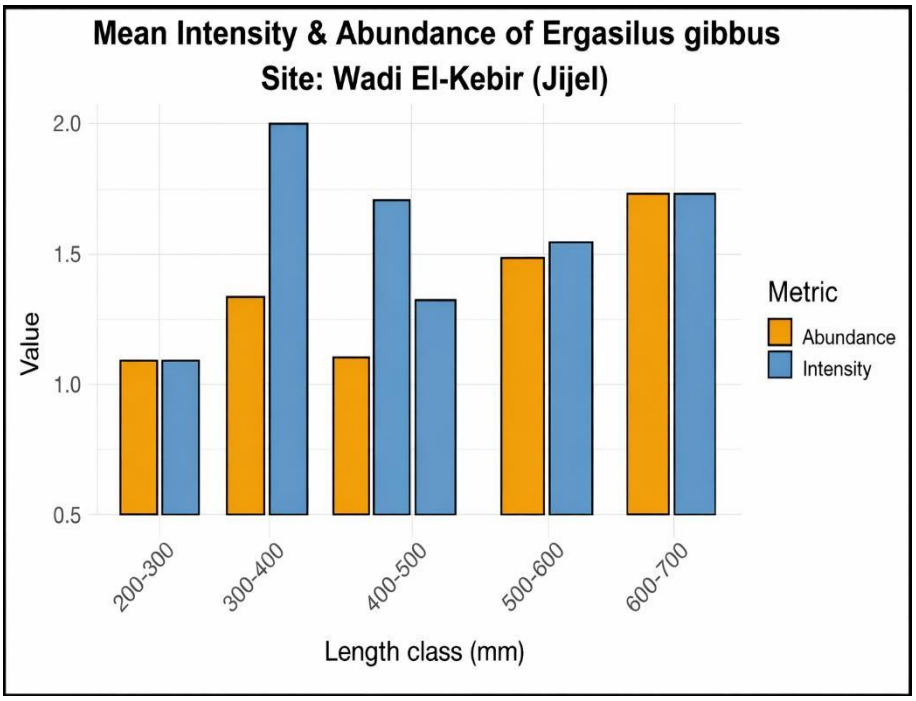

Figure 114: The mean intensity and abundance variation of the *Ergasilus gibbus* at Wadi El-Kebir by length classes.

4.2.17. Seasonal Distribution of the parasitological indices of *Argulus* sp. in Lake Tonga:

- **Prevalence:**

The seasonal prevalence of *Argulus* sp. at Lake Tonga showed marked variation, with spring recording the highest infection rate at approximately 68%. Autumn and winter exhibited similar moderate levels at 16% and 17% respectively, while summer showed the lowest prevalence at approximately 4%, representing a 17-fold difference between peak and minimum values. This pronounced spring peak indicates optimal transmission conditions during this season for the crustacean ectoparasite. (Fig.115).

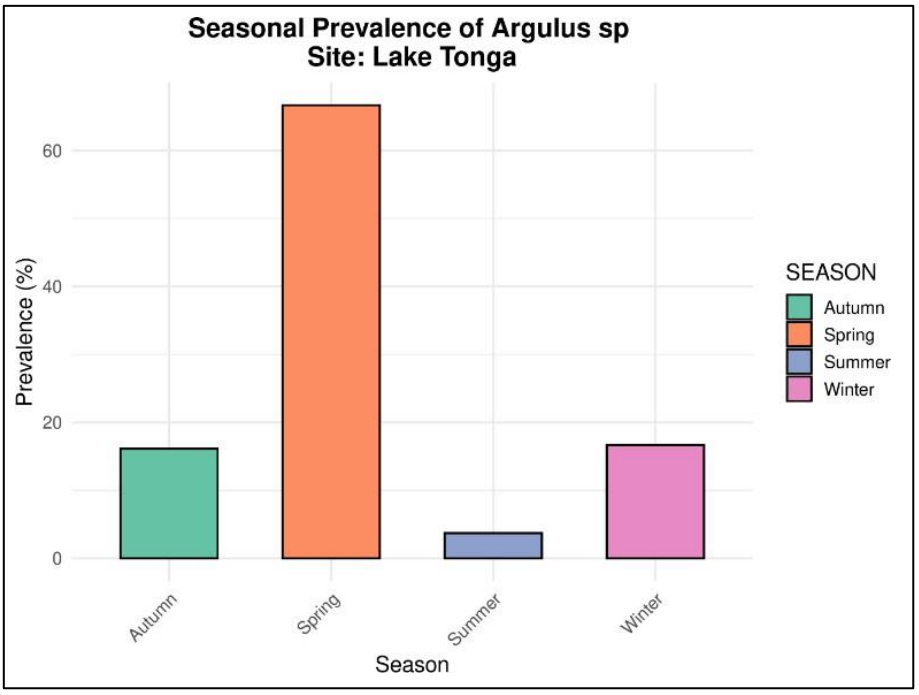

Figure 115: The seasonal variation prevalence of *Argulus* sp. at Lake Tonga.

❖ **Mean intensity and abundance:**

The mean intensity and abundance of *Argulus* sp. at Lake Tonga exhibited strong seasonal variation. The mean intensity was highest in winter, at approximately 2.6 parasites per infected eel, followed by spring at 2.2. Autumn and summer both showed minimal values of 1.0. Mean abundance peaked in spring at 1.5 parasites per examined eel, followed by winter at 0.5, autumn at 0.2, and summer at approximately 0.05. (Fig.116).

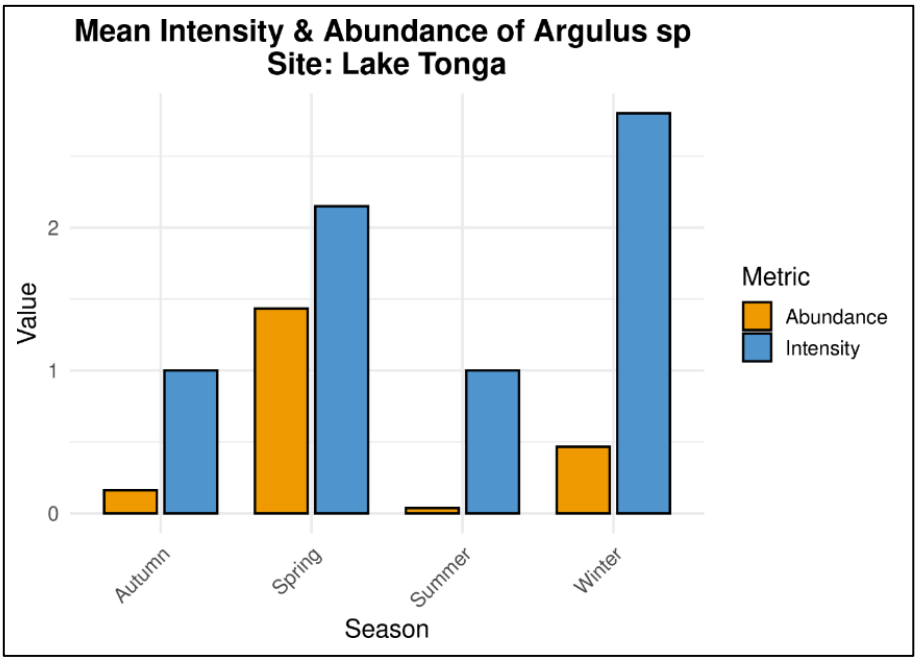

Figure 116: The mean intensity and abundance variation of *Argulus* sp. at Lake Tonga.

4.2.18. Seasonal Distribution of the parasitological indices of *Argulus* sp. in Wadi El-Kebir

- **Prevalence:**

The seasonal prevalence of *Argulus* sp. at Wadi El-Kebir showed relatively stable infection rates across the three seasons sampled. Spring recorded the highest prevalence at approximately 20%, followed by winter at 18.5% and autumn at 16%. (Fig.117).

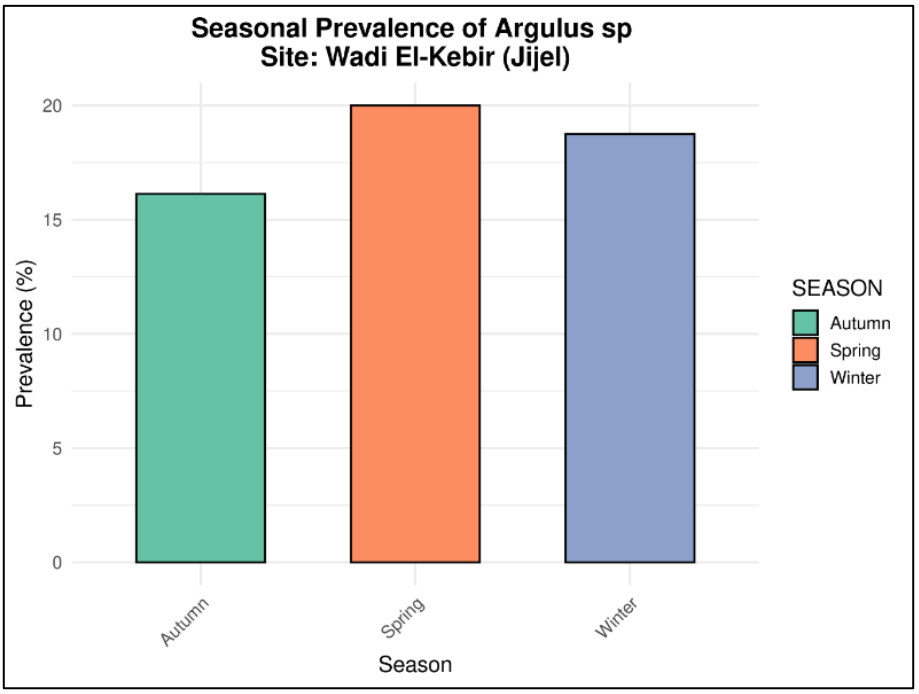

Figure 117: The seasonal variation of the prevalence of *Argulus* sp. at Wadi El-Kebir.

❖ **Mean intensity and abundance:**

The mean intensity and abundance of *Argulus* sp. at Wadi El-Kebir showed progressive seasonal increases. Mean intensity rose from approximately 1.0 parasite per infected eel in autumn to 1.2 in spring and 1.7 in winter. Mean abundance followed a similar pattern, increasing from 0.16 parasites per examined eel in autumn to 0.24 in spring and 0.31 in winter. Winter demonstrated the highest values for both metrics, with intensity nearly doubling and abundance nearly doubling compared to autumn. (Fig.118).

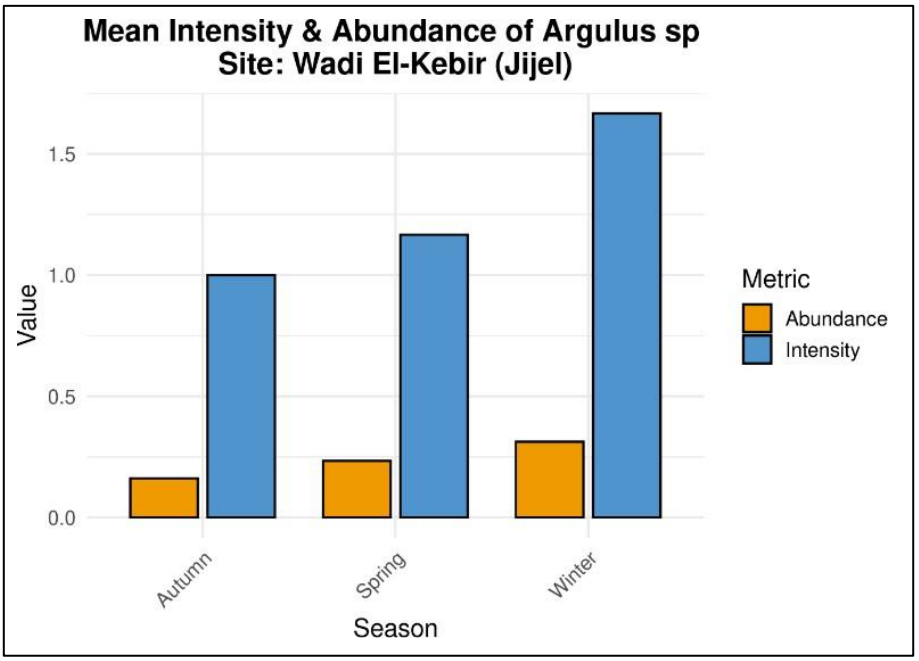

Figure 118: Seasonal variation of the mean intensity and abundance of Argulus sp. at Wadi El-Kebir.

4.2.19. Distribution of the parasitological indices of *Argulus* sp. in Lake Tonga according to length classes:

❖ **Prevalence:**

The prevalence of *Argulus* sp. at Lake Tonga showed a strong positive correlation with eel length class. The smallest eels (300-400 mm) exhibited no infection, while prevalence increased progressively from 23% in the 400-500 mm class to 29% in the 500-600 mm class, 60% in the 600-700 mm class, and reached 100% in the largest length class (700-800 mm). (Fig.119).

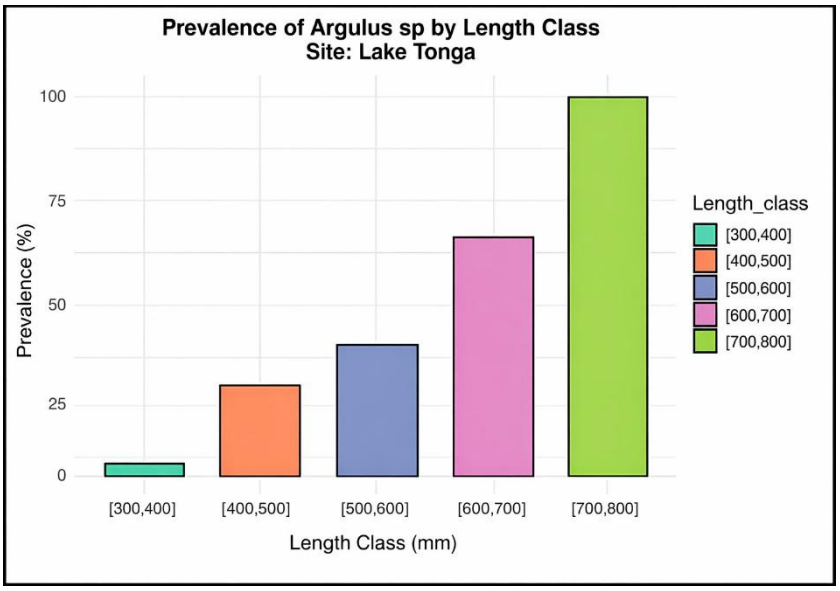

Figure 119:The prevalence variation of *Argulus* sp. at Lake Tonga by length classes.

❖ **Mean intensity and abundance:**

The mean intensity and abundance of *Argulus* sp. at Lake Tonga exhibited a strong positive relationship with eel length class. The smallest eels (300-400 mm) showed no infection for either metric. Mean intensity remained relatively stable at approximately 1.9-2.0 parasites per infected eel across the 400-500 mm, 500-600 mm, and 600-700 mm length classes, then increased sharply to 4.0 in the largest length class (700-800 mm). Mean abundance showed progressive increases from 0.45 in the 400-500 mm class to 0.56 in the 500-600 mm class, 1.4 in the 600-700 mm class, and 4.0 in the 700-800 mm class. (Fig.120).

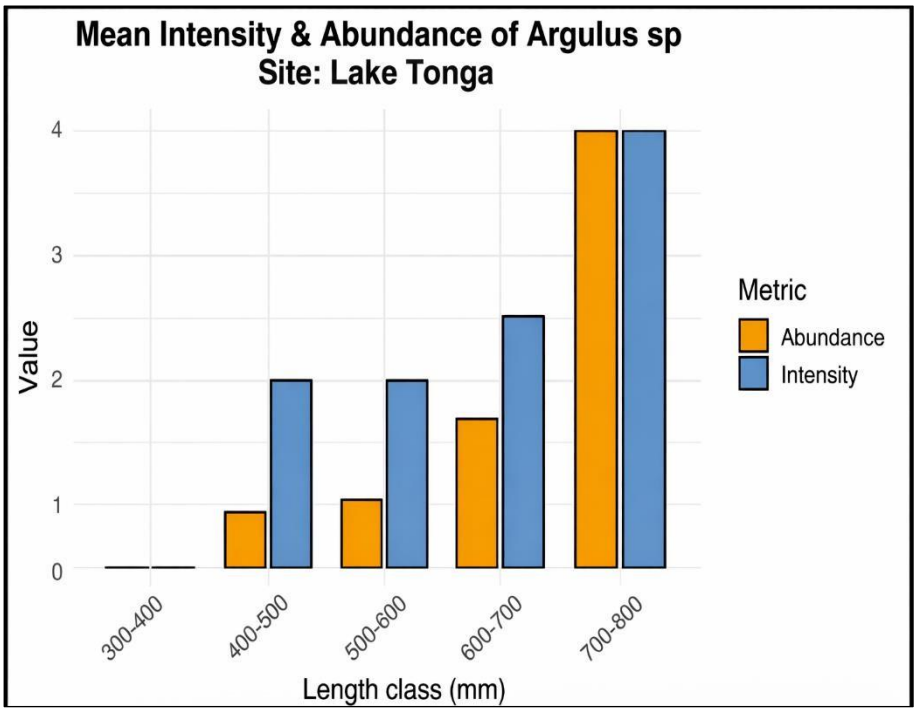

Figure 120:The mean intensity and abundance variation of *Argulus sp.* at Lake Tonga by length classes.

4.2.20. Distribution of the parasitological indices of *Argulus* sp. in Wadi El-Kebir According to length classes:

❖ **Prevalence:**

At Wadi El-Kebir, the prevalence of *Argulus sp.* exhibits a clear positive correlation with eel length, increasing progressively from the smallest to the largest length class. No infection was detected among eels measuring 200–300 mm, suggesting that smaller individuals either avoid infestation due to behavioral or habitat differences or are less susceptible physiologically. Prevalence rises to 17 % and 13 % in the 300–400 mm and 400–500 mm classes, respectively, before increasing sharply in larger individuals—23 % for 500–600 mm and reaching a maximum of approximately 32 % in the 600–700 mm class.(Fig.121).

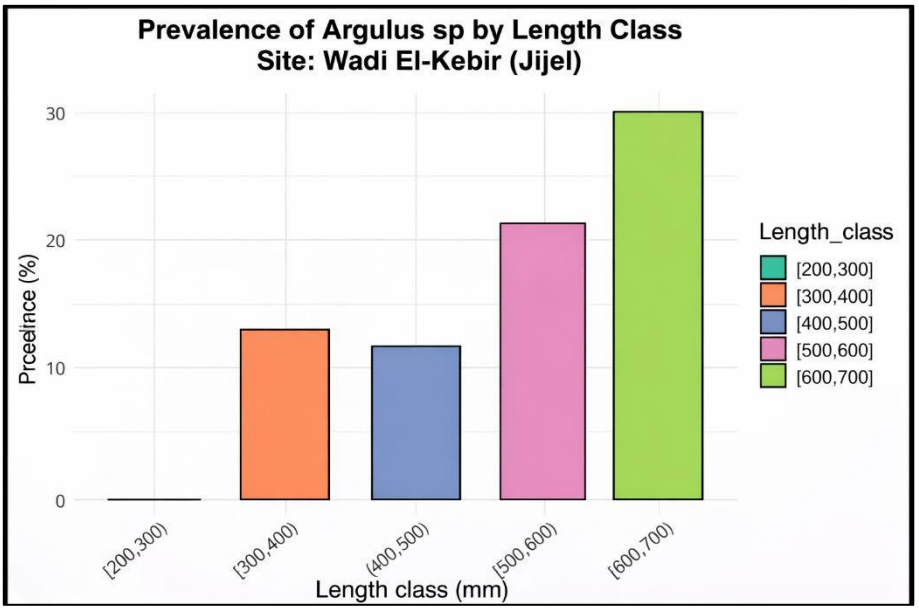

Figure 121: The prevalence variation of *Argulus sp* at Wadi El-Kebir by length classes.

- **Mean intensity and abundance:**

At Wadi El-Kebir, Argulus sp. infection showed clear length dependence. No parasites were found in the smallest eels (200–300 mm), while infection intensity peaked in the 400–500 mm class (~1.65 parasites per infected host) before declining in larger lengths (~1.0 in 600–700 mm). Mean abundance rose gradually from ~0.25 to ~0.45, indicating moderate infection levels. (Fig.122).

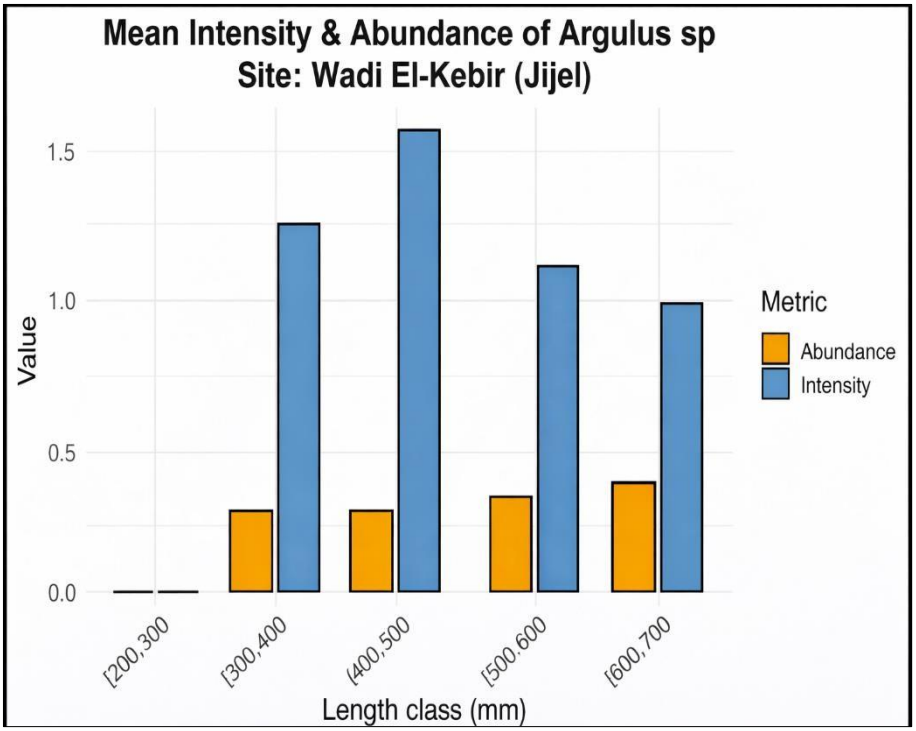

Figure 122: The mean intensity variation *Argulus* sp. at Wadi El-Kebir by length classes.

PART 4: GENERAL DISCUSSION

1. DISCUSSION

In this section, a synthesis of the knowledge acquired throughout this thesis will be presented. The results obtained will be compared with previous findings from the same study site, as well as with data reported from other regions of the Maghreb, the Mediterranean basin, and various parts of the world.

Hypotheses and interpretations will be proposed to explain the observed phenomena and to place them within a broader ecological and biogeographical context.

The discussion will be structured around the following key aspects:

- **Structure of the studied subpopulation**
- **Growth of the studied subpopulation**
- **Feeding habits of the captured eels**
- **Otolithometry**
- **Parasitism**
- **Anguillicolosis**

1.1. Population Structure

During this study, the length and weight-frequency distribution of captured eels in Lake Tonga and Wadi El-kebir ranged from 350 mm to 750 mm total length (TL) and100 g to 900 g, with most individuals concentrated in the 400–450 mm and 450–500 mm classes and in 200–400 g weight class in both sites. These modal groups were especially prominent in Lake Tonga, where over 35 individuals were recorded in the 450–500 mm class. Very few eels exceeded 650 mm in either site, and both populations showed a dominance of medium-sized classes (400–500 mm), with Lake Tonga generally exhibiting higher abundances across most size classes, particularly in the 400–500 mm range.

These findings. are supported by (Tahri et Panfili 2023), which revealed individuals between 170 and 1130 mm TL and 19 to 2642 g, demonstrating the persistence of a wide size structure and the presence of both young and older yellow eels. However, these results are consistent with those reported by Boudjadi (2010), who recorded eels ranging from 310 to 894 mm in length and 42.96 g to 1.9 kg in weight, confirming the predominance of intermediate size categories

In contrast, Tahri (2009) observed smaller individuals in the Mafragh estuary (240–740 mm), while Tahri (2016) also reported similar size ranges but emphasized a higher proportion of small to medium eels, suggesting environmental or trophic constraints specific to coastal estuarine systems.

At a broader geographical scale, eels from Moroccan estuaries exhibit even smaller sizes. El Hilali (2007) and Wariaghli (2013) documented populations from the Sebou and Loukous estuaries dominated by smaller individuals, with total lengths and weights of approximately 200 mm / 12 g (Sebou) and 200–400 mm / 50–200 g (Loukous), respectively.

Across Europe, European eel (Anguilla anguilla) populations display a broad range of length and weight distributions, comparable to those observed in Lake Tonga and Wadi El-Kebir. For instance, studies conducted in Turkish inland waters reported eels measuring between 12.7 and 64.1 cm (127–641 mm) and weighing 3.2 to 416 g, whereas in Greek estuarine systems, individuals ranged from 320 to 991 mm in length and 46 to 2,760 g in weight (İlhan et al.,

2020; Kantzoura et al., 2025). Similarly, in Croatian rivers, most eels fall within the 340–760 mm range, with a marked dominance of individuals around 340 mm, while in French estuaries, lengths typically vary between 215 and 924 mm.(Denis, Mahé, et al. 2022; Piria et al. 2014)

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Seasonal fluctuations in the length and weight of European eels from Lake Tonga and Wadi El-Kebir—characterized by relatively stable mean lengths (400–500 mm) and body weights peaking in spring and autumn (≈230–250 g) but declining in winter (≈120–180 g)—align with patterns observed in other European populations. Research conducted in the Neretva River delta and various European habitats similarly indicates that yellow eels occur throughout the year, with both body size and condition factor reaching their lowest levels in winter and highest in spring and autumn, reflecting seasonal variations in feeding activity, metabolic rate, and energy storage (Marić et al., 2022; Barić et al., 2023).

- **According to the EELREP (2005) classification**, the analysis of sexual maturity stages revealed that the majority of the eels captured were immature (stage I) or early maturing (stage FII). These two categories together represented the dominant portion of both populations, particularly in Lake Tonga, where stage FII individuals were especially abundant. Advanced maturing stages (FIII–FIV) and mature silver eels (stage MII) were comparatively less represented, although a small number of silver eels were recorded at both sites, indicating the onset of the migratory phase.

The sex ratio of European eels in both Lake Tonga and Wadi El-Kebir is clearly skewed toward females, with females accounting for approximately 77% in Lake Tonga (sex ratio 3.3:1 F: M) and 67% in Wadi El-Kebir (sex ratio 2:1 F: M) among sexually differentiated individuals (FII–FIV and MII stages). This strong female predominance is consistent with findings from a 13-year survey in Algeria, which reported that the sex ratio in these North African sites favors females, with silver males maturing early and remaining a minority(Tahri et Panfili 2023)

Such female-biased sex ratios are typical in continental European eel populations, where environmental factors like habitat type, food availability, and population density influence sex determination and tend to favor female differentiation in low-density, high-growth environments such as lakes and large rivers(Geffroy et Bardonnet 2016; Tahri et Panfili 2023)

This pattern is also observed in European studies, confirming that the predominance of females is a widespread phenomenon shaped by ecological conditions across the species' range(Geffroy et Bardonnet 2016)

Research has consistently demonstrated that the average size of female European eels (Anguilla anguilla) at silvering increases with watershed size. In small catchments (<100 km²), females typically reach lengths of approximately 600 mm, whereas those from large river systems frequently exceed 700 mm, and individuals inhabiting lakes or lagoons generally range between 600 and 700 mm (Holmgren et al., 1997; Tahri & Panfili, 2023). Conversely, males silver at considerably smaller sizes, commonly between 348 and 460 mm, with mean silvering lengths reported around 400 mm, while females may attain average sizes exceeding 780 mm (Laffaille et al., 2006; Holmgren et al., 1997).

It is important to note that the proportion of males in field samples is often underestimated, as male downstream migration (avalaison) typically occurs earlier in the season—most frequently in late summer—when sampling efforts are often limited. This temporal bias has been highlighted in recent studies showing that males migrate earlier and exhibit distinct seasonal peaks compared to females (Lagarde et al., 2023).

Overall, these findings reflect sex-specific life-history strategies observed across both North African and European populations, whereby males mature and migrate at smaller sizes and younger ages, while females delay maturation to reach larger body sizes and higher fecundity, enhancing their reproductive potential (Laffaille et al., 2006; Holmgren et al., 1997).

Helfman et al. (1987) suggested that male eels optimize reproductive success by shortening the yellow eel phase, maturing and migrating earlier and at smaller sizes, whereas females extend this phase to attain greater body size and fecundity. Consequently, males generally silver at smaller sizes—rarely exceeding 450–500 mm—while females can reach over 1200 mm. Although both sexes overlap in size and age during early development, mature males remain consistently smaller and younger than females. This sexual dimorphism in growth and maturation reflects distinct life-history strategies that are consistent across both American and European eel populations(Helfman et Bozeman 1984).

Across all latitudes, silver female eels (*Anguilla* spp.) generally exceed 400 mm in length, with smaller migrating females being rare exceptions. Most silver females range between 535 and 931 mm, with an average of about 694 mm, whereas males typically migrate at smaller sizes, usually between 290 and 480 mm, and at younger ages. Females, in contrast, migrate later, between 8 and 18 years depending on the region. Despite this pronounced sexual size dimorphism, body length alone is not a reliable indicator of sex due to the overlap in size and age between males and females, as well as between yellow and silver eels. Although females

are generally larger, this overlap prevents accurate sex determination based solely on size or weight. Therefore, while size dimorphism is a consistent biological trend, it should not be the only criterion used for sex identification in eels(Gray et Andrews 1971).

Macroscopic observation of gonads, especially when combined with size criteria, can effectively distinguish the sexes in silver eels, as most individuals over 400 mm are females; this method has been shown to have low error rates in some populations. However, several studies caution that macroscopic examination alone can be uncertain, particularly in yellow eels or individuals that have not yet fully differentiated, and recommend standardized histological analysis for accurate sex determination, especially in cases of ambiguous or atypical gonadal development. Gonadal differentiation in European eels typically begins between 200–240 mm, but some individuals may remain undifferentiated even at larger sizes and older ages, making size and macroscopic criteria unreliable for all cases(Colombo et Grandidr 1996; Beullens, Eding, Gilson, et al. 1997).

Environmental factors, such as population density and food availability, also influence sex differentiation, further complicating sex identification based solely on external or macroscopic features (Degani et Kushnirov 1992; Colombo et Grandidr 1996; Geffroy et Bardonnet 2016)

Therefore, while macroscopic gonad observation is practical and generally reliable for silver eels, histological examination remains the gold standard for precise sex determination, particularly in research or management contexts where accuracy is critical (Colombo et Grandidr 1996; Beullens, Eding, Gilson, et al. 1997).

Experimental studies on Anguilla anguilla confirm that environmental factors—especially population density and food availability—strongly influence sex differentiation. High densities and limited resources favor the development of males, while lower densities and better conditions promote the development of females; this pattern is also observed in Anguilla rostrata , Some individuals may undergo sex reversal in response to environmental pressures, demonstrating significant sexual plasticity that helps eels adapt to variable habitats(Davey et Jellyman 2005; Geffroy et Bardonnet 2016). The mechanism of sex determination in eels remains unresolved: while some chromosomal evidence (such as possible ZZ/ZW systems) exists, most research indicates that sex is primarily determined by environmental cues, with genetic factors possibly playing a polygenic role (Davey et Jellyman 2005; Geffroy et Bardonnet 2016) Temperature and salinity have been proposed as influencing factors, but experimental results are inconsistent, and no clear effect has been established for either . Sex

ratios in eel populations are highly variable, but female dominance is frequently observed in both freshwater and estuarine environments, likely due to faster growth rates and delayed maturation in females compared to males (Davey et Jellyman 2005; Geffroy et Bardonnet 2016; Krueger et Oliveira 1999)

The ocular index (OI) appears to be a useful criterion for assessing the degree of transformation in eels. This index has the advantage of being non-destructive, as it does not require sacrificing individuals. However, it is essential to standardize measurement procedures to minimize inter-observer variability. Moreover, eye development—or ocular hypertrophy—is accompanied by several structural changes in the retina, such as a reduction in cone cell density, which represents an adaptation to life in deeper or low-light aquatic environments(Pankhurst et Lythgoe 1983).

Artificial maturation experiments have demonstrated that the ocular index (OI) in eels can reach values as high as 27, confirming its sensitivity to advanced stages of silvering and physiological transformation. An OI threshold of 6.5 has been proposed as the minimum value marking the onset of migration, with eels above this threshold considered migratory; among these, individuals under 500 mm are typically males, while those 500 mm or larger are females. More recent studies suggest a slightly higher threshold of 8.0 for migration readiness. Research confirms that eels with an ocular index (OI) greater than 6.5 are considered migratory, with those under 500 mm in length typically being males and those 500 mm or longer being females. More recent studies have proposed raising this migration threshold to an OI of 8.0, reflecting refinements in the criteria for identifying migratory individuals. Consistently, yellow eels exhibit lower average OI values than silver eels, supporting the OI as a reliable indicator of maturation and migration status (Acou et al. 2005)

The threshold value of the ocular index (OI) used to characterize eels that have begun their downstream metamorphosis (silvering) varies among authors. Fontaine (1994) reported that non-silvered (yellow) eels have an average OI of 4.33 (range: 2.94–5.70), while fully silvered eels that have completed all three stages of silvering show an average OI of 8.48 (range: 5.58–11.4). He suggested that yellow eels with an OI above 5.6 are likely to have initiated silvering and will probably migrate within the year.

Other studies have proposed different thresholds: Pankhurst (1982) identified an OI of 6.5 as the minimum value for migratory eels, while more recent research recommends a threshold of 8.0 to distinguish silver eels(Acou et al. 2003a; Pankhurst et Lythgoe 1983)

According to the Eye Index, the majority of eels from Lake Tonga (85%) were identified as being in the silver stage, while 15% remained in the yellow stage. In contrast, at Wadi El-Kebir, silver eels represented 60% of the population, with yellow eels comprising 40%. Spatial comparisons of the ocular index (OI) reveal notable differences in both mean values and the proportion of silver eels across sites, suggesting the influence of local environmental and demographic conditions. For example, in Valle Campo Lagoon (Italy), only around 28% of individuals were silver females, with significant OI differences observed between yellow and silver stages but not among advanced silvering phases.(Emmanuele et al. 2019). Therefore, a multicriteria approach—combining OI with qualitative indicators like lateral line development and skin coloration—is recommended for more accurate and standardized identification of silver eels across locations (Acou et al. 2005)

Before their final migration, eels undergo a transformation called silvering, which prepares them for deep marine conditions. This process involves significant morphological changes, notably the enlargement of the eyes (measured by the ocular index, OI) and the pectoral fins (measured by the pectoral fin index, ILP), both of which can be tracked to assess the progression from the yellow (resident) to the silver (migratory) stage (Demirci 2024a; Durif et al. 2005; 2009) The ILP increases from less than 4% in yellow eels to 5% or more in silver eels, enhancing swimming efficiency for transoceanic migration (Durif et al. 2005; Demirci 2024b) Eye size and pectoral fin length are reliable external markers of silvering, and their measurement allows for accurate classification of eels' migratory readiness (Demirci 2024a; Durif et al. 2005; 2009)

Nearly half of the eels captured at both sites were classified as indeterminate according to the Pectoral Fin Index (PFI).

a predominance of intermediate-stage eels characterizes both sites, but Wadi El-Kebir exhibits a higher proportion of both silver and yellow eels, while Lake Tonga maintains a slightly more homogeneous distribution centered on intermediate **individuals**.

1.2. Growth:

The negative allometric growth observed in Lake Tonga eels (b = 2.83) indicates that as these eels increase in length, they become relatively more slender, with body weight increasing at a slower rate than the cube of their length. This pattern aligns with findings from other regions, such as the Krueng Sawang River in Indonesia and the Tigris and Murat Rivers in Turkey, where eels also exhibited negative allometric growth (b values ranging from 2.73 to 2.75) (Mulyadi et al., 2025; Koyun et al., 2023; Shefat, 2021). In contrast, the nearly isometric growth recorded in Wadi El-Kebir (b = 2.95) suggests that eels there maintain their body proportions as they grow. This observation is comparable to results from certain riverine populations of spiny eels in India and European eels in Turkish inland waters, where b values were close to or slightly above 3, reflecting isometric or even slightly positive allometric growth (Pathak et al., 2013; İlhan et al., 2020; Mohd, 2015).

Eel growth and sexual maturation are closely linked, with growth rates typically declining as individuals approach sexual maturity. Research shows that sexual maturation in eels is influenced by both environmental and physiological factors, such as temperature, photoperiod, and hormonal regulation. For example, cold seawater pre-treatments and simulated migration conditions can accelerate sexual maturation and induce key biometric and hormonal changes in European eels, bringing farmed individuals to a maturity state similar to wild migrants (Ferrão et al. 2024; Mes et al. 2016)

The onset of downstream migration is associated with a cessation of feeding and the start of sexual maturation, with exercise and migration itself stimulating early maturation, as indicated by changes in eye size, oocyte growth, and fat deposition in oocytes (Palstra et al. 2011)

Body size is a key trigger for the onset of metamorphosis (silvering) in European eels (Anguilla anguilla), with similar findings in Japanese eels (A. japonica), where a critical length—typically around 50–67 mm for leptocephali—must be reached before metamorphosis can occur, regardless of age or environmental conditions (Fukuda et al. 2018; Okamura et al. 2014)

In American eels (A. rostrata), fecundity in silver-stage females increases with body size, supporting the idea that larger individuals have greater reproductive potential.

There is considerable variability in length–age and length–weight relationships among eels, even within the same habitat, sex, and length class, leading to notable differences in weight between individuals(Beullens, Eding, Ollevier, et al. 1997; Demirci 2024c)

. Direct measurement of weight is more reliable than estimation, though minor biases can occur if yellow eels have recently fed heavily; these can be corrected using established adjustment factors(Nowosad et al. 2014)

The Gonado-Somatic Ratio (GSR%) is a key parameter for evaluating gonadal development and sexual maturity in European silver eels (*Anguilla anguilla*) during their downstream migration. The process of "silvering," which marks the transition from the yellow (resident) to the silver (migrating) stage, encompasses a series of progressive physiological transformations, notably gonadal development, ocular enlargement, and changes in skin reflectivity. However, these internal changes are not always accompanied by clearly visible external alterations such as pigmentation shifts.

Threshold GSR values—greater than 0.2% for males and greater than 1% for females—are widely accepted as indicators of sexually mature, migrating individuals, in line with established diagnostic criteria, although specific GSR measurements are not always reported in detail. Studies have shown that the rate and extent of gonadal development can vary considerably among individuals, influenced by factors such as body size, age, and physiological condition (Durif *et al.* 2005, 2006).

Research by Pankhurst and Lythgoe (1983) demonstrated that while integumentary characteristics, including structure and pigmentation, change silvering, these modifications result primarily from the redistribution of purine crystals rather than from alterations in pigment composition. Consequently, coloration—although useful for distinguishing yellow from silver eels—is not a reliable indicator of sexual maturity, given the subjectivity of color assessment and the lack of correlation between melanophore density and gonadal stage.

During downstream migration (*dévalaison*), eels are sexually differentiated but not yet fully mature. Gonadal mass increases significantly during metamorphosis; however, complete sexual maturity is typically achieved only after migration to marine environments, potentially under the influence of hydrostatic pressure (Pankhurst & Lythgoe, 1982). Earlier studies further suggest that gonadal development begins early in the metamorphic process, followed by morphological and physiological changes such as eye enlargement, skin pigmentation adjustments, and regression of the digestive tract. These transformations are accompanied by

modest increases in gonadotropin hormone levels in freshwater, which correlate with gonad weight (Pankhurst 1982; Pankhurst & Lythgoe 1983).

In the present study, the Gonadosomatic Index (GSI) values ranged from **0.05 to 2.0**, with the lowest values recorded at **Wadi El-Kebir during winter** and the highest during **spring**, while **Lake Tonga** showed moderate and relatively stable values between

Furthermore, a positive correlation was observed between GSI and total length at both sites, indicating that larger eels exhibit more advanced gonadal development. This relationship was moderate at **Lake Tonga** ($R^2 = 0.41$) but stronger at **Wadi El-Kebir** ($R^2 = 0.70$), suggesting a clearer size-dependent maturation pattern at the latter site. Moreover, GSI was also positively correlated with the Ocular Index (OI), with coefficients of determination of **$R^2 = 0.33$** at Lake Tonga and **$R^2 = 0.70$** at Wadi El-Kebir, confirming a consistent association between gonadal development and eye enlargement during silvering.

Multiple studies confirm a positive correlation between the Gonadosomatic Index (GSI) and both total length and Ocular Index (OI) in eels, supporting the observation that larger individuals and those with greater eye enlargement exhibit more advanced gonadal development. For example, research on Japanese eels found that GSI and OI were significantly higher in well-developed, hormonally responsive individuals, and that OI was positively correlated with GSI in both sexes(Han et al. 2006)

Similarly, studies on European eels demonstrated a significant correlation between increased eye area and GSI, with both indices rising progressively during the silvering process and serving as reliable markers of maturation(Acou et al. 2003b; Jéhannet et al. 2019)

These findings indicate that the relationship between body size, eye enlargement, and gonadal development is consistent across different eel species and habitats, although the strength of the correlation may vary by location and population structure(Han et al. 2006; Acou et al. 2003b)

This supports the use of GSI and OI as complementary, objective indicators of maturation during the silvering phase in eels.

Research on the American eel (*Anguilla rostrata*) in the St. Lawrence River system corroborates these findings. According to Jéhannet *et al.* (2019), migrating (silver) eels exhibit significantly higher Gonadosomatic Index (GSI) values (**2.1–3.7%**) and larger mean oocyte diameters (**0.100–0.210 mm**) compared to resident (yellow) eels, which display lower GSI (**0.3–0.7%**) and smaller oocytes (**0.049–0.072 mm**). These parameters—GSI and oocyte size—serve as reliable indicators of migratory readiness and reproductive development, with oocyte

diameter thresholds of **0.07–0.085 mm** often used to define the onset of migration in specific regions. Moreover, GSI and oocyte diameter tend to increase with age and during the migration season, reflecting progressive gonadal maturation. Larger individuals generally possess more developed ovaries, as evidenced by strong correlations between ovary width and body size. In addition, elevated plasma levels of **17β-oestradiol** parallel increases in GSI and oocyte diameter, highlighting the close association between physiological and morphological maturation during the migratory phase.(Ccottrill et al. 2001)

The liver plays a crucial role in eel metabolism and undergoes significant structural changes during the transition from yellow to silver stages, particularly involving the accumulation and later mobilization of lipid reseves. The Hepatosomatic Index (RHS%) in silver eels can range from 0.5% to 5%, influenced by sex and individual variation, and typically decreases as eels prepare for migration due to cessation of feeding and utilization of stored energy(Lecomte-Finiger 1994)

Although the provided research does not directly quantify lipid reserves, it supports the importance of the liver in metabolic adaptation and highlights that physiological changes, including liver mass and function, are closely linked to the silvering process and migration readiness in eels(Fazio et al. 2012)

During this study, **The Hepatosomatic Index (HSI)** showed clear seasonal variation at both sites. At **Lake Tonga**, values ranged from **0.8–3.1%**, peaking in **summer** and lowest in **spring**; at **Wadi El-Kebir**, HSI varied between **1.0–2.8%** with a similar trend. About half of the eels had HSI values below **1.5%**, reflecting **metabolic adjustments linked to the silvering and migration process**.

Seasonal variation in the Hepatosomatic Index (HSI) of eels is well-documented, with studies showing that HSI values fluctuate throughout the year, often peaking in warmer months and declining during periods associated with migration and silvering. For example, research on European eels found that HSI was higher in silver-stage eels compared to yellow-stage eels, reflecting increased liver size and energy storage in preparation for migration(Demirci 2024c) Other studies confirm that eels exhibit marked seasonal changes in liver-related biomarkers, with the most pronounced shifts occurring in summer, likely due to elevated temperatures and metabolic demands(Gorbi et al. 2005) Additionally, about half of the eels in some populations have HSI values below 1.5%, which is consistent with metabolic adjustments linked to the cessation of feeding and mobilization of energy reserves during the silvering and migration process(Gorbi et al. 2005; Demirci 2024c).

The Empty Gut–Somatic Index (EGSI%) confirmed that nearly all eels from both Lake Tonga (approximately 95%) and Wadi El-Kebir (approximately 92%) were in the silvering stage. Seasonal variation showed that at Lake Tonga, the highest EGSI% values occurred in winter (around 4.8%) and summer (around 4.2%), with the lowest values in autumn (approximately 2.6%). Likewise, at Wadi El-Kebir, peaks were observed in winter (around 4.5%) and spring (around 4.0%), with autumn showing the lowest values (about 2.5%) and greater variability.

These findings align with established research on eel silvering, which describes the transformation from the yellow to the silver stage preceding migration. Silvering is characterized by morphological and physiological changes, including digestive tract regression, cessation of feeding, and metabolic reorganization that conserves energy for long-distance migration. Histological studies confirm digestive system degeneration during silvering, but individual and environmental variability may cause some eels to retain feeding activity temporarily.

The observed seasonal EGSI% peaks correspond to periods when silvering intensifies, consistent with literature reporting shrinkage of the alimentary tract and increased mobilization of energy reserves. Lower autumn values reflect advanced silvering stages and the functional shutdown of non-essential systems to optimize migration efficiency(Peters 1982).

The seasonal variation of the growth coefficient (k) at Lake Tonga and Wadi El-Kebir (Jijel) shows distinct trends when examining mean values. At Lake Tonga, the mean growth coefficient is lowest in winter at about 1.65, increases to approximately 2.0 in spring, dips slightly to around 1.9 in summer, and rises again to about 2.0 in autumn. At Wadi El-Kebir (Jijel), the mean k in winter is roughly 1.75, peaks in spring at about 2.0, is not available for summer, and returns to around 1.75 in autumn. These patterns indicate that growth is generally more pronounced in spring and autumn at both sites, while it is somewhat reduced during winter, with possible sampling gaps in summer at Wadi El-Kebir. Overall, the seasonal means of k reflect periods of heightened metabolic and growth activity likely tied to environmental conditions and the physiological state of the eels. Outliers in each season also confirm notable individual variability in growth rates within populations.

The analysis of the condition factor (K) supports this pattern of seasonal variation. According to(LADJAMA IMENE 2016), the monthly K values for eels from Lake Tonga ranged between **1.47 and 1.91** during the first annual cycle and between **0.99 and 1.92** during the second. In

contrast, eels from the lagoon showed K values oscillating between **0.86 and 1.89** during the first cycle and between **1.10 and 1.71** during the second. The seasonal averages revealed higher K values in **autumn and winter**, suggesting that eels exhibit their best somatic condition during these periods, possibly due to increased lipid storage before migration.

These observations are consistent with those reported by (Tahri M. 2016) in Lake Oubeïra, where eels exhibited relatively high K values ranging from **1.69 to 1.89** during the first sampling campaign and from **1.78 to 2.26** during the second. Tahri (2016) further noted a **positive correlation between K and both length and weight**, indicating that larger individuals tend to maintain higher energy reserves. Conversely, (BOUDJADI 2010), working in the Mafrag region, reported a **weak relationship between K and size, weight, or age**. However, he observed that both small and large eels, as well as heavier and older individuals, displayed relatively high condition factors.

Seasonal variation in the growth coefficient (k) of eels is influenced by environmental factors, particularly temperature and food availability, and shows distinct patterns across different habitats. Research on European eels demonstrates that growth rates are generally higher during periods with favorable temperatures, such as spring and autumn, and tend to decrease in winter

when metabolic activity is lower due to colder conditions (Jellyman 1997; Vaughan et al. 2021; Panfili et al. 1994). These trends are consistent with findings from multiple sites, where growth is most pronounced in spring and autumn, reflecting heightened metabolic and growth activity, while winter is associated with reduced growth(Vaughan et al. 2021; Mu et al. 2021) Individual variability in growth rates is also notable within eel populations, influenced by factors such as age, sex, habitat, and local environmental conditions**.** Outliers in seasonal growth data further confirm that not all individuals respond uniformly to environmental cues, highlighting the complexity of growth dynamics in eel populations (Panfili et al. 1994; Jellyman 1997)

1.3. DIET:

The diet of the different population groups examined in this study was assessed using several parameters: the analysis of the eels' feeding habits was based on the calculation of the vacuity coefficient (CV%), determined by evaluating the prey items present or absent in the digestive tract, as well as the frequency of occurrence of prey (F%).

The analysis of the vacuity coefficient (CV%) revealed notable seasonal and size-related differences between the two study sites. On average, **eels from Wadi El-Kebir (≈68%)** exhibited a higher vacuity coefficient than those from **Lake Tonga (≈51%)**, suggesting reduced feeding activity and a greater proportion of individuals with empty digestive tracts in the former population.

At **Lake Tonga**, seasonal CV% values ranged from about **20% in summer** to **85% in autumn**, with intermediate levels during **winter (~65%)** and **spring (~35%)**. The overall mean CV% (≈51%) indicates a moderate and seasonally variable feeding activity, with the lowest gut emptiness recorded in summer, likely corresponding to increased prey availability and higher metabolic activity under favorable thermal conditions.

At **Wadi El-Kebir (Jijel)**, the CV% varied between **40% in spring** and **90% in autumn**, while winter showed intermediate values around **75%**. The higher mean CV% (≈68%) reflects lower feeding intensity, possibly associated with environmental constraints or a higher proportion of silver-stage eels preparing for migration, when feeding activity naturally declines.

These results are in line with previous findings by **Tahri (2016)** and **Djebbari (2012)**, who also reported higher vacuity coefficients during warm periods and lower ones during colder seasons, suggesting a strong influence of temperature on feeding activity. For instance, **Tahri (2016)** recorded the lowest CV values at the end of winter and in spring, and the highest in summer, linking this pattern to the inhibitory effect of high temperatures on feeding. Similarly, **Vøllestad et Jonsson (1988)** and **Tesch (1993)** observed that eels tend to reduce or stop feeding during thermal extremes, with **Bruun (1963)** and **Nyman (1972)** noting normal feeding between **13–17°C**, while it ceases below **8–10°C**.

In comparison, our results from **Lake Tonga** indicate an opposite trophic dynamic, with the lowest CV (~20%) recorded in summer and the highest (~85%) in autumn. This inverse pattern may reflect interannual or site-specific variations in temperature, prey availability, or

physiological state of the eels, suggesting that environmental and ecological factors play a key role in modulating feeding activity across years and habitats.

These numbers suggest that feeding activity is highest in summer and spring, likely due to increased prey availability and favorable temperatures, and lowest in autumn and winter, possibly due to environmental constraints or a higher proportion of silver-stage eels preparing for migration, when feeding naturally declines. Seasonal and site differences in CV% reflect the eels' adaptability to local conditions and their opportunistic feeding behavior, as supported by research showing that eels adjust their diet and feeding intensity in response to environmental changes. Seasonal changes in feeding indices, including CV%, have been observed in other Mediterranean and European habitats, further supporting the link between environmental conditions and eel feeding behavior. Additionally, studies highlight that eels adapt their diet and feeding intensity to local conditions, and that individual and population-level variability in CV% is common, reflecting the species' flexible and opportunistic feeding strategies (**Teichert et al., 2023; Bouchereau et al., 2006**).

In both sites, feeding activity showed a clear size-related pattern. Smaller eels (200–300 mm) exhibited very low vacuity (0–10%), indicating active feeding. Medium-sized individuals (300–700 mm) showed higher and more stable gut emptiness, with vacuity values ranging between **55% and 65% at Lake Tonga** and **65% to 94% at Wadi El-Kebir**, reflecting reduced feeding activity. In contrast, the largest eels (700–800 mm) displayed **0–100% vacuity**, suggesting either limited sample sizes or distinct feeding behavior at advanced stages. Overall, vacuity increased with size, supporting the idea that feeding intensity declines as eels approach the **silvering stage**.

Size-related differences in feeding behavior and gut emptiness among eels are well supported by research. Smaller eels (such as the 300–400 mm class at Lake Tonga) often have the lowest percentage of empty guts, reflecting more frequent or successful feeding, while medium-sized eels (400–700 mm) may show higher rates of gut emptiness (55–60%), possibly due to dietary shifts or increased competition. The largest eels (700–800 mm) at Lake Tonga with 0% empty guts suggest highly efficient feeding or a shift to larger, more energy-rich prey, as larger eels are known to become more piscivorous and may feed less frequently but on bigger meals , At Wadi El-Kebir, the sharp increase in empty gut percentages with size, peaking at 94.4% in the 400–500 mm class and reaching 100% in the 600–700 mm class, may indicate a transition to less frequent feeding, possibly related to preparation for migration or changes in habitat use.

Research shows that as eels grow, their diet shifts from small invertebrates to larger prey, and their feeding periodicity and microhabitat use also change, with larger eels often feeding at different times or in different locations than smaller ones(Jellyman 1989; Sagar et Glova 1998; Glova et Jellyman 2000) Additionally, feeding efficiency and prey selection are influenced by mouth size and sensory abilities, with smaller eels able to exploit a wider range of prey sizes, while larger eels become more selective and efficient predators(Sagar et Glova 1998; Knights 1983).

The diet composition of European eel (Anguilla anguilla) shows significant variation between habitats, reflecting their opportunistic and adaptable feeding strategies. At Lake Tonga, fish dominate the diet (36%), indicating a strong piscivorous tendency, followed by algae (23%), crustaceans (12%), unidentified gut content (8%), and vegetation (7%). In contrast, at Wadi El-Kebir, crustaceans are the most significant prey (29%), with fish (17%), algae (16%), vegetation (12%), and unidentified material (9%) making up the rest, suggesting a more varied and opportunistic diet influenced by local prey availability.

Research supports that the European eel's diet is shaped by the abundance and type of local food resources, with eels in different habitats (marine, brackish, freshwater) showing distinct dietary profiles and flexibility in prey selection(Verhelst et al. 2025; Denis, Rabhi, et al. 2022; Parzanini et al. 2021) In estuarine and brackish environments, eels often consume a mix of crustaceans and fish, with the specific proportions varying by site and environmental conditions(Denis, Rabhi, et al. 2022; Parzanini et al. 2021) This dietary plasticity allows eels to thrive in diverse habitats and adapt to changes in prey availability, which is crucial for their survival and condition across their complex life cycle (Verhelst et al. 2025; Denis, Rabhi, et al. 2022; Parzanini et al. 2021)

The diet composition of *Anguilla anguilla* revealed clear ecological differences between the two habitats, confirming the species' opportunistic and adaptive feeding behavior. At **Lake Tonga**, fish constituted the main prey category (36%), followed by algae (23%), crustaceans (12%), unidentified material (8%), and vegetation (7%), highlighting a predominantly piscivorous trend. These results are consistent with **Djebbari (2012)** and **Ladjama Imène (2016)**, who also observed that eels from freshwater habitats such as Lake Tonga consumed mainly fish and plant matter (about 80%), with crustaceans and insects making up a smaller portion of their diet (around 20%).

Conversely, in **Wadi El-Kebir**, crustaceans represented the most important food item (29%), followed by fish (17%), algae (16%), and vegetation (12%), indicating a more diversified and opportunistic feeding strategy influenced by prey availability and local environmental conditions. Similar trends were reported by **Boudjadi (2010)** at Mafrag and **Tahri (2016)** at Lake Oubeïra, where eels showed a clear preference for animal-origin prey, particularly fish and crustaceans. Overall, these findings confirm that **eel diet composition is strongly shaped by habitat type**, with a predominance of fish in freshwater environments and a greater contribution of crustaceans and mixed prey in brackish waters, reflecting the high trophic plasticity of the species.

1.4. OTOLITHOMETRY:

Estimating the age and growth of European eels is challenging due to their complex biology and the wide variety of habitats they occupy, which result in highly variable growth patterns. The most reliable method for age estimation is otolithometry—reading growth rings on otoliths (ear stones)—since scalimetry (using scales) is unreliable due to the late appearance and irregular growth of eel scales (Panfili et al. 2022; Moriarty 1983; Durif et al. 2020).

To date, no comprehensive investigation has addressed the growth of the internal skeleton (skeletochronology) in eels, with otoliths remaining the principal structure employed for age determination. Nevertheless, the absence of a standardized preparation protocol persists, as comparative methodological studies have yielded conflicting, inconclusive, or even contradictory outcomes regarding the most reliable approach (Vøllestad and Næsje, 1988; Panfili and Ximénès, 1992; Durif et al., 2020).

Techniques such as burning and cracking, grinding and polishing, and sectioning with staining have all been used, but each can yield different age estimates, and the choice of grinding plane or preparation method can introduce bias (Graynoth 1999; Véró et al. 1986; Panfili et Ximénès 1992; Durif et al. 2020)

The age of eels inhabiting Lake Tonga and Wadi El-Kebir (Jijel) was determined through otolith analysis. A total of **180 pairs of otoliths** were successfully extracted from **213 specimens**. Owing to the distinct visibility of their growth increments, the otoliths were **directly observed under a binocular dissecting microscope** using **reflected light on a black background**, with the structures **immersed in ethanol** to improve contrast and facilitate age reading.

The "in toto" method for eel otolith observation, which involves immersing whole otoliths in clearing solutions like alcohol, xylene, or oils and examining them under a dissecting microscope, has been a standard technique for age and growth studies in yellow eels for many decades. This approach was widely used in the late 20th century and remains common in more recent research, although newer methods such as grinding and polishing for age estimation have also been adopted to improve accuracy, especially in older or slow-growing eels (Durif et al. 2020)

In European eel (Anguilla anguilla) research, assigning a standardized "birthday" is a common practice to facilitate age determination and comparison across studies. According to European norms, the birth date is typically set at June 1st for all sampled individuals, as referenced by (Panfili et al. 2002). However, earlier work by (Frost 1945) used May 1st as the date for age class change (the "anniversary") in this species.

(Sinha et Jones 1967) also applied this method, although various other reference dates have been used, making direct comparisons between studies difficult and often requiring uncertain adjustments. They suggested that, rather than selecting an arbitrary date, the number of years spent in freshwater should be inferred from the growth marks visible on the otoliths. This would yield region-specific reference dates corresponding to the different arrival periods of glass eels. However, such an approach does not resolve the issue of comparability, and adopting a single standardized date appears more appropriate.

(Helfman et Bozeman 1984) proposed April 1st as the reference date for Anguilla rostrata, which approximately corresponds to the beginning of the spawning season.

Moreover, the estimated duration of the marine phase for glass eels reaching coastal waters varies widely. For Anguilla anguilla, reported estimates range from 2–3 years (Schmidt, 1922), 3 years(Liew 1974) , 2–7 years (Van Utrecht et Holleboom 1985) 11–18 months (Boëtius & Harding, 1985), 7–11 months (Lecomte-Finiger et YAHYAOUI 1989), and 191–276 days (Lecomte-Finiger 1992) In contrast, the American eel (Anguilla rostrata) is thought to have a shorter marine stage, estimated at 10–12 months (Schmidt, 1922), 2 years (Liew, 1974), or 8–12 months (Kleckner et McCleave 1985).

Across both sampling sites, eel ages ranged from **1 to more than 6 years**, with a **mean age of approximately 3.0 years**. The overall age structure was dominated by young and intermediate individuals (1–4 years), while older eels (>5 years) were less represented, indicating a population largely composed of recent recruits with limited representation of older age classes.

These results are consistent with the findings of These results are consistent with the findings of Tahri (2016), who reported that the age of eels sampled from Lake Oubeïra ranged from 1.5 to 6.5 years, with a mean age of 4 years. The same authors later reported in 2023 a mean age of 2 ± 0.6 years and an overall range of 0.7 to 6.6 years for eels inhabiting Algerian waters. This similarity suggests comparable growth dynamics and recruitment patterns across the studied Algerian sites. Research on European eels (Anguilla anguilla) in Morocco confirms significant age variation depending on the site. According to Wariaghli (2013), eel ages in the

Sebou and Loukous regions range from 3 to 13 years, with a mean age of 6 years for all samples studied.

The diversity of techniques used to examine eel otolith growth structures and the lack of validation for these methods contribute to uncertainty in interpreting age and growth data. This methodological variability may partly explain the observed differences in eel growth across the European eel's geographic range, but environmental factors such as temperature, habitat type, food availability, eel density, and competition also play significant roles (Vaughan et al. 2021; Panfili et al. 1994; Jellyman 1997; Yokouchi et al. 2012) . For example, temperature strongly influences growth rates, with optimal growth occurring within specific thermal ranges and both low and high extremes leading to reduced growth or increased deformities(Politis et al. 2017; Vaughan et al. 2021)

Additionally, individual growth variability is marked in eels, with factors like sex, age, and size at marking affecting growth rates, and high intra- and inter-population variability in length at a given age is common(Panfili et al. 1994; Jellyman 1997; Yokouchi et al. 2012). Habitat productivity, density-dependent competition, and annual temperature cycles further contribute to growth differences, and even within a single population, there can be substantial overlap in size among age classes (Panfili et al. 1994; Jellyman 1997; Yokouchi et al. 2012; Boulenger et al. 2016)

- **Semi-direct validation:**

Semi-direct validation is a method used to estimate the age of fish, such as eels, by observing growth marks on otoliths (ear stones), either qualitatively (e.g., hyaline or opaque margin) or quantitatively (measuring marginal zones) across many individuals sampled over time. This approach is crucial because accurate age estimation depends on correctly identifying these growth marks and understanding their formation periods, but for eels, such studies are rare due to their occupation of highly diverse habitats(Panfili et al. 1994)

- For example, (Dekker 1986) vital marking experiment using tetracycline encountered major difficulties related to recapture rates and the observation of otoliths, which limited its effectiveness. Two additional tetracycline-marking experiments conducted in pond environments (Panfili et Ximénès 1992) provided a clearer understanding of the periodicity and formation rhythms of otolith increments, thereby contributing

valuable insights into eel **Age validation studies:**

During this study at both sites, **opaque edges predominate throughout the year. This dominance is especially pronounced in winter, when opacity reaches its highest levels — exceeding 90% at Lake Tonga and up to 94% at Wadi El-Kebir**.

Similar findings were reported by **Tahri (2016)**, who observed that the percentage of opaque zones remained very high regardless of the sampling month, exceeding **77% during the first campaign** and **75% during the second**.

The timing and formation of otolith growth zones are closely linked to environmental parameters, particularly temperature and salinity. Experimental studies show that otolith growth in eels and other fish species increases with rising water temperatures, with optimal growth typically occurring between 22°C and 26°C, and growth ceasing at temperatures below 10°C (Fukuda et al. 2009)

Salinity also influences otolith chemistry and growth, but its effects are often intertwined with temperature, making it challenging to isolate the individual impacts of each. For example, higher temperatures generally promote faster otolith growth and clearer increment formation, while changes in salinity can alter the incorporation of elements like strontium and barium into the otolith, further complicating the interpretation of growth marks (Miller 2011; Nelson et al. 2018; Izzo et al. 2018)

The relationship between these physico-chemical factors is complex, as they often interact and are influenced by additional variables such as food availability and metabolic rate(Miller 2011; Wenger et al. 2016; Izzo et al. 2018). Studies emphasize that both environmental and physiological factors must be considered when analyzing otolith growth patterns, and that direct age estimation from otoliths is most reliable when these influences are well understood and validated under controlled conditions (Fukuda et al. 2009; Izzo et al. 2018)

Most studies conducted on eels have provided **qualitative results** without reporting mean values (Sinha & Jones, 1967a; Lee, 1979; Lecomte-Finiger, 1985). The qualitative results reported by Fernandez-Delgado et al. (1989) for an estuarine environment and by (Panfili 1993) for a Mediterranean lagoon and freshwater canal are similar. The latter study clearly demonstrates an **annual cycle of formation of opaque and hyaline zones**: deposition of the opaque zone may begin as early as autumn. In contrast, formation of the hyaline zone occurs during summer. However, the precision regarding the timing of formation (time intervals) is limited, and there is a noticeable **shift between lagoon and freshwater environments**.

Individual variability is considerable, and a certain percentage of otoliths display **margins that are difficult to interpret**. Moreover, **100% opaque margins are never observed**, as marginal opacity is only visible when the opaque zone is already well developed. This type of validation therefore requires monitoring over a period exceeding one year to reveal **cyclic phenomena that vary between years and among individuals**. These results are consistent with those obtained using **vital marking techniques** (Panfili et al., 1992).

Sinha and Jones (1967a) observed that, in **yellow eels of *Anguilla anguilla*** from England, the opaque mark appeared at the **beginning of August**, while the translucent mark formed **after November**.

The period of deposition of the "summer" mark extended over five months. However, the exact onset of the deposition of the "winter" mark remains open to interpretation.

Finally, the use of the terms **"winter" and "summer"**—by analogy with structures observed on scales—is not entirely appropriate for describing the growth zones on eel otoliths, although these terms are commonly used. The deposition of these zones extends over **more than one season**, and unlike scales, which exhibit a distinct cessation of growth during the cold season, **otoliths continue to grow at a slower rate**. The use of the terms **opaque and translucent zones** is therefore preferable and more directly applicable to the discontinuities observed under optical microscopy (transmitted or reflected light) (Fortin et faune 2001)

1.5. Parasitism

1.5.1. Parasite diversity:

The assessment of the parasitic fauna of eels captured in Lake Tonga and Wadi El-Kebir (Jijel) revealed the presence of **six parasite species**, including **two crustaceans** (*Ergasilus gibbus* and *Argulus* sp.), **one monogenean** (*Pseudodactylogyrus* sp.), **one cestode** (*Bothriocephalus claviceps*), and **two nematodes** (*Anguillicoloides crassus* and *Hysterothylacium* sp.).

Ergasilus and Argulus are parasitic crustaceans recognized as significant pathogens in freshwater fish, including economically important aquaculture species. Argulus, in particular, is known to cause severe tissue damage, inflammation, immunosuppression, and even death in infected fish, leading to substantial economic losses in aquaculture, such as the reported $62.5 million loss in the Indian sector(Haridevamuthu et al. 2024; Shameena et al. 2021) Both parasites feed on the epithelial tissues of their hosts, often targeting the gills, which can result in hypotrophy (underdevelopment) of gill filaments, impaired respiration, and osmoregulatory dysfunction, especially under stressful environmental conditions(Haridevamuthu et al. 2024; Paperna 2013; Eaves et al. 2014).

Pseudodactylogyrus anguillae and *Pseudodactylogyrus bini* are monogenean parasites that exhibit strict host specificity to the European eel (*Anguilla anguilla*). Their global distribution has been largely facilitated by the international trade of eels (Køie, 1991; Hayward et al., 2001). Morphologically, the two species can be differentiated based on the size and configuration of their haptor (attachment organ), with both employing specialized hooks and adhesive secretions to anchor firmly to the gill tissues of their host (Arafa & Reda, 2011). Previous studies have demonstrated that *P. anguillae* and *P. bini* may coexist on the same individual, sharing similar microhabitats within the gill apparatus. Their spatial distribution appears to be determined primarily by gill architecture rather than by seasonal variations or the specific gill arches they occupy (Dzika, 1999; Matějusová et al., 2003; Zolovs et al., 2016). Seasonal peaks in infection intensity are generally recorded during the warmer months, coinciding with optimal reproductive temperatures of approximately 20°C (Zolovs et al., 2016).

Research on helminth parasite communities in the European eel (Anguilla anguilla) indicates that these assemblages generally exhibit low species diversity and are frequently dominated by a single taxon, often an acanthocephalan, across both freshwater and brackish environments throughout Europe (Sures et al., 1999; Bakaria et al., 2018a). The cestode Bothriocephalus claviceps is widely distributed across continental European waters and is commonly found in the intestinal tract of European eels. Its prevalence and abundance show limited seasonal variation, although peaks in body size and reproductive activity are typically observed during the summer months (Nie & Kennedy, 1992; Bakaria et al., 2018b). B. claviceps is regarded as a specific parasite of eels (Anguilla spp.) within the Holarctic region, with its distribution closely mirroring that of its hosts, being reported in both European and North American anguilliform species (Scholz, 1997; Scholz et al., 2004; Dupont & Gabrion, 2004a). The life cycle of B. claviceps involves copepods as the first intermediate hosts. It may include paratenic

hosts such as perch and guppies, with eels typically acquiring infection in estuarine habitats before their migration into freshwater environments (Dupont & Gabrion, 2004b).

Studies investigating parasite diversity in European eels (*Anguilla anguilla*) from Mediterranean lagoons have reported relatively high species richness, with ten species identified in France, ten in Spain, and up to twenty-three macroparasite species recorded across several French lagoons. These assemblages include representatives of the classes *Monogenea*, *Digenea*, *Cestoda*, *Nematoda*, *Acanthocephala*, and *Crustacea* (Fazio et al., 2005; Maillo et al., 2005; Fazio et al., 2008). For instance, ten parasite species were identified in the Salses-Leucate lagoon in southern France, and similar levels of diversity were observed in Spanish coastal lagoons (Maillo et al., 2005; Fazio et al., 2005). These results suggest that parasite richness in Mediterranean lagoons is generally higher than that recorded in other regions, such as in our study area—Lake Tonga, Wadi El-Kebir, and Lake Oubeïra—where parasite diversity appears comparatively low. The observed variation in species richness likely reflects local ecological conditions specific to each lagoon, as well as the influence of invasive species such as *Anguillicoloides crassus* and *Pseudodactylogyrus* spp., which may further shape the composition and structure of parasite communities (Fazio et al., 2008).

Long-term investigations of parasite communities in European eels (*Anguilla anguilla*) remain scarce, as most existing studies are short-term and focus primarily on specific parasites such as *Anguillicoloides crassus*. An eight-year study conducted in Austria revealed that cultured eel populations exhibited low parasite diversity and were typically dominated by a single species, a pattern also observed in wild populations from England. This reduced diversity has been attributed to intraspecific competition, limited resource availability, and host immune responses, which together often result in individual eels harbouring only one or two trematode species (Abdallah & Mâamouri, 2006). The dominant parasite species in eel populations appear to vary geographically: *Pseudodactylogyrus anguillae* predominates in the Ebro Delta, *Deropristis inflata* and *Bucephalus polymorphus* are common in Italian lagoons, *Anguillicoloides crassus* is prevalent in the Languedoc-Roussillon region, and *Bucephalus anguillae* dominates in Tunisian lagoons, where its life cycle is completed within brackish environments (Abdallah & Mâamouri, 2002; Abdallah & Mâamouri, 2006).

Here is a summary table of parasite species reported in European eels (Anguilla anguilla) from the Mediterranean

Table 8: Summary of Parasite Species Reported in European Eel (Anguilla anguilla)

Parasite Group	Species (examples)	Country / Location	Reference
Monogenea	*Pseudodactylogyrus sp.*	Algeria (Lake Tonga, El Mellah Lagoon)	Bakaria et al., 2018
Cestoda	*Bothriocephalus claviceps*	Algeria (Lake Tonga)	Bakaria et al., 2018
Nematoda	*Anguillicoloides crassus*	Algeria (Lake Tonga, Oubeira, Mafrag); Morocco (Sebou estuary); Tunisia	Tahri Mardja et al., 2017; Djebbari et al.; Loukili & Belghyti, 2007; Gargouri Ben Abdallah & Maamouri, 2006
Nematoda	*Cucullanus sp.*	Algeria (Lake Tonga, El Mellah Lagoon)	Bakaria et al., 2018
Crustacea	*Ergasilus gibbus, Argulus foliaceus*	Algeria (Lake Tonga, El Mellah Lagoon)	Bakaria et al., 2018
Monogenea	*Pseudodactylogyrus anguillae, P. bini*	France, Corsica, Spain, Turkey	Kennedy, 2007; Moravec, 2009; Dezfuli et al., 2002; Öztürk, 2021
Digenea	*Bucephalus anguillae, Deropristis inflata, Lecithochirium musculus*	France, Corsica, Italy	Kennedy, 2007; Moravec, 2009; Dezfuli et al., 2002
Cestoda	*Proteocephalus macrocephalus, Myzophyllobothrium sp.*	France, Corsica, Turkey	Kennedy, 2007; Moravec, 2009; Dezfuli et al., 2002
Nematoda	*Contracaecum sp., Gnathostoma sp.*	France, Corsica, Spain, Egypt, Turkey	Kennedy, 2007; Moravec, 2009; Dezfuli et al., 2002; Al-Zanbagi, 2005; Öztürk, 2021

Acanthocephala	***Acanthocephalus anguillae, Acanthocephaloides incrassatus***	**France, Corsica**	**Kennedy, 2007; Moravec, 2009**

1.5.2. Parasitic indices:

Among the six parasite taxa identified in *Anguilla anguilla* from Lake Tonga and Wadi El-Kebir (Jijel), *Pseudodactylogyrus sp.* was the most dominant species in terms of prevalence, mean intensity, and mean abundance at both sites. At Lake Tonga, *Pseudodactylogyrus sp.* showed the highest prevalence (63.9%), mean intensity (3.71), and abundance (2.37), followed. Similarly, at Wadi El-Kebir, *Pseudodactylogyrus sp.* (63.4%; 3.36; 2.13) with Winter showed the highest infection rate, reaching approximately 80%

Tahri (2009) reported between **89 and 200 specimens per infected eel** and **65 to 193 specimens per examined eel**. However, during the period when the mean temperature was around **15°C (from December to May)**, the *Pseudodactylogyrus* load did not exceed **48 specimens per infected eel** and **less than 42 specimens per examined eel**.

Pseudodactylogyrus species are widely recognized as the **most dominant gill parasites** of the European eel (*Anguilla anguilla*) across multiple regions, including **Lake Tonga** and **Wadi El-Kebir**, where **prevalence rates frequently exceed 60%** and may reach **up to 80%** during certain seasons, particularly in winter. These observations are consistent with findings from other geographical areas, such as **Turkey**, where *Pseudodactylogyrus anguillae* exhibited a **prevalence of 82.2%** and a **high mean intensity of infection**, confirming its predominance among eel parasites (Çolak & Soylu, 2012).

Seasonal variation in *Pseudodactylogyrus* infection is well documented. In many cases, **higher infection rates occur during colder months** or under specific environmental conditions, although some studies have reported **infection peaks in warmer periods**, depending on local ecological factors. The **abundance and prevalence** of *Pseudodactylogyrus* species, particularly *P. anguillae* and *P. bini*, are significantly influenced by **environmental parameters** such as **temperature, habitat type, and seasonality**. Elevated parasite loads are generally recorded during **warmer months**, with **prevalence and abundance peaking in late summer** and declining during cooler periods. This pattern supports the hypothesis that

temperature exerts a major influence on parasite reproduction and egg development, with **optimal hatching occurring around 30°C** (Nie & Kennedy, 1991; Barker & Cone, 2000; Buchmann, 1989). In European eels from various regions, prevalence can range widely, sometimes reaching 100% in certain localities, and abundance is often higher in brackish or freshwater habitats with suitable conditions(Fazio et al. 2008) Studies in both wild and cultured eels confirm that water temperature, pH, and flow rate all affect parasite levels, with higher temperatures and lower flow rates favoring greater infestations(Barker et Cone 2000; Zhang et al. 2015)

Low dissolved oxygen (DO) levels, or hypoxia, are well-documented to induce stress in fish leading to increased plasma cortisol and catecholamine levels, which can suppress immune function and make fish more susceptible to parasitic infections. Multiple studies confirm that hypoxia impairs both innate and adaptive immune responses, including reduced lymphocyte activity, downregulation of immune-related genes, and decreased phagocytic function, resulting in higher disease susceptibility and mortality (Wang et al. 2018; Abdel-Tawwab et al. 2019; Franke et al. 2024)

Water quality, particularly **dissolved oxygen (DO)**, plays a key role in regulating parasite prevalence in aquatic environments. **Hyperoxia** (high DO levels) can **reduce the habitable surface area** for gill parasites and thereby **lower infection rates**, as reported in several studies (Linh et al., 2023). Conversely, **poor oxygenation** has been consistently linked to **higher parasitic prevalence in aquaculture systems** (Ageng'o et al., 2024).

The crustacean *Ergasilus gibbus* exhibited clear **seasonal and size-related variations**. At **Lake Tonga**, infection peaked in **winter (77%)** and was minimal in **summer (4%)**, while at **Wadi El-Kebir**, **spring (75%)** showed the highest prevalence. **Larger eels** were more heavily infected, with **100% prevalence** in the largest size class, indicating that **host size and environmental factors** jointly shape parasite dynamics.

These results are consistent with previous studies showing that *E. gibbus* infections in *Anguilla anguilla* vary significantly with **season and host length**. Research from **Mediterranean coastal lagoons in France** reported that both the **occurrence and intensity** of *E. gibbus* infections are influenced by **seasonal patterns** and **eel size**, with higher prevalence and abundance observed in **spring or winter** and among **larger individuals** (Filippi et al., 2013). This pattern aligns with broader ecological evidence indicating that **older and larger eels**

generally harbor more parasites due to **longer exposure and greater gill surface area** (Conneely & McCarthy, 1986). Therefore, the **seasonal peaks** and **size-dependent infection rates** recorded at both study sites are consistent with established trends in **European eel populations** (Conneely & McCarthy, 1986; Filippi et al., 2013).

In Spain, studies have reported very low infestation rates of Ergasilus gibbus in European eels (Anguilla anguilla). For example, Maillo et al. (2005) found a prevalence of only 7.7% and an abundance of 0.59 parasites per eel examined in the Ebro Delta, while other surveys in Spanish coastal lagoons reported prevalence rates between 1.55% and 3.5%, with mean intensities ranging from 1.29 to 7.4 parasites per infected fish(Maillo et al. 2005)

Argulus sp. exhibited marked seasonal variation, with peak prevalence in spring (≈68%) at Lake Tonga, followed by a sharp decline to ≈4% in summer. Infection intensity and abundance were also highest in spring and winter, suggesting favorable conditions for parasite transmission during these periods. At Wadi El-Kebir, prevalence remained relatively stable, showing only a slight winter increase when both mean intensity (≈1.7) and abundance (≈0.31) reached their maxima. According to Tahri (2016), *Argulus* sp. infected 13% of eels collected in December 2010 during the first sampling campaign and persisted throughout the second, with infection rates ranging from 4% to 70%. The parasite was absent in eels from the Mafrag estuary (Tahri, 2009). In Lake Tonga,(Djebbari N. 2012) reported infestation rates between 3.6% and 13.5%. Overall, infestation by parasitic copepods appears relatively low, consistent with findings from Algerian coasts(Ramdane et Trilles 2007), Tunisian waters (Benmansour et al. 2001). and French populations (Ternengo et al. 2005)

The only cestode found in our investigation was *Bothriocephalus claviceps* Goeze, 1782, a parasitic member of the Bothriocephalidae family that mostly infects the European eel's gut. (Nie & Kennedy, 1991) This species is widespread. A scolex with bothridia is one of its defining features. According to Nie and Kennedy (1991) and Scholz (1997), B. claviceps is a heteroxenous parasite that needs a cyclopoid copepod as its only intermediate host.

Bothriocephalus claviceps exhibited marked seasonal variation across both sites. At Lake Tonga, prevalence peaked in spring (≈50%) and declined to ≈23% in summer, while mean intensity and abundance reached their highest levels in winter (3.0 and 1.35, respectively). At Wadi El-Kebir, prevalence was highest in spring (≈72%) and lowest in winter (≈18%), with intensity peaking in winter (4.6) and abundance in spring (1.

according to tahRi 2016: Infestation rates of Bothriocephalus claviceps in European eels (Anguilla anguilla) show considerable geographic and seasonal variation. In North African sites like Mafrag, prevalence is generally low (less than 7%), with the highest value (16.7%) recorded in June when water temperatures reach 24.8°C, and overall rates never exceeding 34% during two sampling campaigns, with autumn showing the highest values. This pattern is supported by observations from Camargue, France, where seasonal and temperature-related dynamics are also reported, and by broader literature noting that increased temperatures stimulate cestode reproduction and boost populations of copepod intermediate hosts.

In Spain, Maillo et al. (2005) found B. claviceps to be present in eels from three Ebro Delta lagoons, but with relatively low prevalence compared to other helminths, and did not report rates as high as those seen in some North African or French sites, Other studies in Spain and Europe also indicate that B. claviceps prevalence and intensity are generally modest, and that infection levels are influenced by local environmental factors, especially temperature and seasonality, which affect both parasite reproduction and intermediate host abundance(Maillo et al. 2005; Dupont et Gabrion 2004)

othriocephalus claviceps infections in Anguilla anguilla demonstrate notable seasonal and size-related variation, but the patterns can differ by location. Research from Mediterranean coastal lagoons in France and long-term studies in Austria indicate that parasite occurrence and abundance are influenced by both season and eel size, with larger eels generally harboring more parasites, consistent with the 100% prevalence observed in the largest size classes at Lake Tonga and Wadi El-Kebir(Schabuss et al. 2004; Filippi et al. 2013)

However, some studies in southwest England found no statistically significant seasonality in prevalence or abundance, though the cestode's growth and reproduction peaked in summer, and new generations were recruited during this period(Nie et Kennedy 1992)

A round, hematophagous (blood-feeding) worm of the genus Hysterothylacium is a type of nematode parasite commonly found in marine and freshwater fish. These parasites are often difficult to identify to the species level due to their morphological similarities, so researchers frequently use both morphological and molecular methods, such as sequencing of rDNA ITS and mtDNA cox2 genes, for accurate identification . Hysterothylacium larvae can infect various tissues in fish, including the digestive tract and sometimes internal organs, and are known to be widespread in edible fish species in regions like the Black Sea While Hysterothylacium species are primarily known as fish parasites, their hematophagous nature

refers to their ability to feed on the blood or tissues of their hosts, which can impact fish health and food safety. Molecular characterization is essential for distinguishing between closely related species and understanding their distribution and potential risks to fisheries and consumers(Gelen et Pekmezci 2023)

The infestation of eels by the nematode *Hysterothylacium* sp. exhibited marked seasonal variation at both study sites. At Lake Tonga, prevalence fluctuated between 30% and 60%, reaching its maximum in spring (mean intensity ≈ 3.3; abundance ≈ 2.1) and declining to below 10% during winter. A similar trend was observed at Wadi El-Kebir, where prevalence peaked in spring (≈ 43%) and dropped to approximately 13% in winter, accompanied by parallel seasonal variations in mean intensity and abundance.

Research on the European eel (*Anguilla anguilla*) in Algeria has documented the presence of the nematode *Cucullanus* sp. in several localities, including the Mellah Lagoon, Lake Tonga, Lake Oubeïra, and the Mafragh Estuary. In the Mellah Lagoon, *Cucullanus* was detected in the digestive tract of eels, while at Lake Tonga its prevalence was very low, with only one infected eel recorded in April (0.3%) (*Bakaria et al.*, 2018). In Lake Oubeïra, prevalence remained low throughout the year (not exceeding 6.66%), and infected individuals typically harbored a single worm. Conversely, in the Mafragh Estuary, prevalence exceeded 20% in February and March, and infected eels hosted up to 5.1 worms, with abundance ranging from 0.03 to 1.2—higher than those recorded in Oubeïra (0.3–0.6). These findings highlight substantial spatial and temporal variability in *Cucullanus* sp. infestations, suggesting that both site-specific and seasonal factors influence infection dynamics (*Bakaria et al.*, 2018).

In Spain, *Aguilar et al.* (2005) reported the presence of *Cucullanus heterochrous*, with infestation rates ranging from 9.3% to 17% and mean intensities between 3.3 and 4.3 parasites per infected fish. Similarly, *Køie* (2000) identified *Cucullanus cirratus* in the pyloric caeca and intestine of Atlantic cod (*Gadus morhua*).

1.6. Anguillicolosis

❖ **Parasitic indices of Anguillicoloides crassus:**

The genus *Anguillicola* (currently encompassing *Anguillicoloides*) comprises five species of parasitic nematodes that infect eels, among which *Anguillicoloides crassus* is particularly notable for its invasive capacity and pathogenic impact. *A. crassus* is native to East Asia, where the Japanese eel (*Anguilla japonica*) serves as its natural host, and was first described in Japan in 1974. Genetic and historical evidence indicate that East Asia—particularly within the distribution range of *A. japonica*—is the most probable origin of *A. crassus*, although some uncertainty remains due to possible earlier introductions related to aquaculture practices in Japan (*Lefebvre et al.*, 2012; *Laetsch et al.*, 2012).

The parasite was introduced into Europe in the early 1980s, most likely through the importation of Japanese eels for aquaculture purposes. Since then, it has rapidly spread across Europe and North America, infecting multiple *Anguilla* species and posing a serious threat to native eel populations (*Lefebvre et al.*, 2012; *Laetsch et al.*, 2012; *Wielgoss et al.*, 2008). Molecular and population genetic analyses suggest that the European invasion originated from a single introduction event from Taiwan, followed by rapid geographic expansion and genetic drift, whereas North American populations are genetically more closely related to Japanese stocks (*Wielgoss et al.*, 2008; *Laetsch et al.*, 2012).

The pathogenicity of *A. crassus* is markedly higher in the European eel (*Anguilla anguilla*) than in its native host, leading to significant swimbladder damage, altered gas composition, and reduced migratory performance—factors that may further endanger this already critically threatened species (*Würtz et al.*, 1996; *Heitlinger et al.*, 2013). Moreover, the tendency for host switching and invasive expansion appears to be a general characteristic within the Anguillicolidae, raising concerns regarding the global translocation of eels and their associated parasites (*Laetsch et al.*, 2012).

Anguillicoloides crassus infection in eels, particularly the European eel (Anguilla anguilla), leads to significant pathological changes in the swimbladder, including inflammation, hemorrhages, epithelial erosion, and thickening of the swimbladder wall, which can severely impair its function(Dezfuli et al. 2021; Innal et al. 2019) This damage is associated with reduced swimming speed, increased energy and oxygen consumption during migration, and may ultimately prevent successful migration to spawning grounds, raising concerns about reproductive success (Kirk 2003; Currie et al. 2020; Dezfuli et al. 2021) While the parasite load and swimbladder damage can remain constant during prolonged periods in saltwater, the infection does not appear to affect resistance to hydrostatic pressure(Currie et al. 2020; Unger et al. 2024a)

genetic studies indicate that Mediterranean populations of A. crassus are distinct from Atlantic populations, suggesting separate introduction events (Unger et al. 2024a) . The parasite has also been reported in North America and the Indian Ocean, infecting various Anguilla species, with evidence that new hosts such as the European and American eels experience more severe pathology than the parasite's original host, the Japanese eel, where clinical disease and mortality are rare (Kirk 2003) Notably, eels with severe swimbladder damage may paradoxically show greater body size, possibly due to increased foraging activity and repeated parasite exposure, but this does not mitigate the negative effects on migration and fitness(Lefebvre et al. 2013)

The prevalence of *Anguillicoloides crassus* in European eels (*Anguilla anguilla*) from Lake Tonga showed clear seasonal variation, peaking in winter (≈68%) and reaching its lowest level in summer (≈48%), a difference of about 20 percentage points. Mean intensity and abundance followed the s ame pattern, with maximum values in winter (4.9 and 3.3, respectively) and minimum values in autumn (2.3 and 1.3).

At Wadi El-Kebir, prevalence remained consistently high across seasons (58–67%), with the highest levels in winter and the lowest in autumn. Mean intensity (5.5) and abundance (3.7) also peaked in winter, declining sharply during spring and autumn.

A strong size-related pattern was observed at both sites. At Lake Tonga, prevalence rose from 17% in small eels (300–400 mm) to nearly 100% in individuals larger than 600 mm, indicating cumulative infection with age. Mean intensity and abundance increased correspondingly, reaching 6.0 parasites per eel in the largest size class.

At Wadi El-Kebir, infection followed a bimodal distribution: both the smallest (200–300 mm) and largest (600–700 mm) eels were fully infected (≈100%), while mid-sized classes showed lower prevalence (≈44–70%). Mean intensity and abundance mirrored this trend, with high values in small and large eels and lower values in intermediate sizes.

Djebbari (2012) reported the presence of this parasite in two water bodies of the El Kala National Park. In Lake Tonga, it is present throughout the year, whereas in the Mellah Lagoon, its occurrence is limited to eight months out of twelve, with infestation rates not exceeding 5%. The infestation levels recorded for *Anguillicola crassus* in Lake Tonga are six times higher than those observed in the lagoon. Tahri (2009) reported parasitic indices in the Mafrag estuary of P = 50%, I = 4 worms per infected swim bladder, and A = 2.05 worms per examined fish.

In Morocco, a rapid spread of the parasite was observed along the Atlantic coast in 1994, followed by its extension to the Mediterranean coast in 1997. The introduction of cyprinids is believed to be responsible, as no eel importations were recorded(Kheyyali et al. 1999). More recently, (El Hilali 2007) reported a prevalence of 55.36% and an intensity of 1.92 parasites per swim bladder in the Sebou estuary. Finally, in Tunisia, (Abdallah et Maamouri 2006) recorded infestation rates of 7.26% with an average of 1.06 parasites per swim bladder in the Ichkeul Lagoon.

In the Vaccarès Lagoon, Lefebvre *et al.* (2002) recorded an abundance of 4 parasites, a prevalence of 70%, and a mean intensity ranging from 4 to 6 parasites during July of 1997, 1998, 1999, and 2000. Similar results were reported by Fazio (2007) in the same lagoon in July 2004, with a prevalence of 77% and a mean intensity of 6.5 parasites. In the Mauguio Lagoon, Benajiba *et al.* recorded a prevalence ranging from 30% to 40% and a mean intensity of 3 parasites during July 1988 and 1989.

Salinity appears to be a key factor influencing the development and survival of the parasite. Indeed, parasite survival—whether at the free-living L2 stage or the adult stage (Kirk et al. 2000)—declines as salinity increases. Under laboratory conditions, the parasite can survive and be transmitted in marine environments (50% and 100% seawater) for up to six months, suggesting its potential to endure during transatlantic migration (Kennedy and Fitch, 1990; Kirk *et al.*, 2000b). *A. crassus* is thus capable of tolerating a wide range of salinities (Kirk *et al.*, 2000a; Maillo *et al.*, 2005).

(Benajiba et al. 1994) showed that seasonal variations in salinity and temperature in natural environments (Mauguio Lagoon) do not seem to affect the life cycle of *A. crassus*. (Lefebvre

et al. 2003) demonstrated a negative correlation between parasitic indices (prevalence, mean intensity, and mean abundance) in silver eels and salinity, with a prevalence of 52% in brackish water compared to 77% in freshwater. Similarly, in southern Brittany, prevalence was higher in low-salinity environments (>90%) than in estuarine conditions (15%) (Sauvaget et al. 2003)(Sauvaget *et al.*, 2003). The same trend was observed in four Tunisian lagoons (Gargouri Ben Abdallah and Maamouri, 2006).

Anguillicoloides crassus exhibits low host and habitat specificity, enabling it to thrive across diverse freshwater environments and to exploit multiple species throughout its life cycle. The main intermediate hosts are copepods, particularly *Cyclops* species and the *Acanthocyclops robustus–americanus–vernalis* complex. However, the parasite can also utilize ostracods such as *Physocypria nipponica*, as well as amphibians, aquatic insects, and certain fish species as paratenic (transport) hosts that are subsequently ingested by eels, facilitating infection (Moravec *et al.*, 2005; Ashworth *et al.*, 1996). This ecological flexibility allows *A. crassus* to establish rapidly in new environments, particularly where favorable temperatures and abundant paratenic hosts (e.g., carp) are present (Ashworth *et al.*, 1996; Moravec *et al.*, 2005; Moravec & Škoríková, 1998).

Following its introduction, *A. crassus* typically spreads rapidly within eel populations, with both prevalence and intensity rising sharply before stabilizing at relatively high yet steady levels, as shown in long-term studies across Europe. For example, in Northern Germany, infection rates and parasite intensities peaked during the first decade after introduction, subsequently declining and stabilizing over the following decades, suggesting the establishment of a host–parasite equilibrium. This pattern of rapid expansion followed by stabilization has been consistently reported throughout Europe, reflecting both the parasite's ecological adaptability and the eventual balance achieved with its eel hosts.(Unger et al. 2024b)

During the present study, the temporal dynamics of *Anguillicoloides crassus* infestation in Lake Tonga and Wadi El-Kebir were consistent with the patterns reported by Tahri in Lake Oubeïra, where a high prevalence (exceeding 60%) was recorded between November and February. During this period, the water temperature in Lake Oubeïra ranged from 11°C to 25°C (Azeroual, 2003), which is comparable to the thermal conditions observed in Lakes Tonga and Jijel. These findings are further supported by those of Tahri (2009) in the Mafrag estuary, who reported elevated mean values of both intensity and abundance during the winter and spring seasons. Similar seasonal trends have also been documented in analogous environments in

Morocco (Rahou et al., 2001), Tunisia (Gargouri Ben Abdallah and Maamouri, 2006), and France (Lefebvre et al., 2002).

experimental studies confirm that low temperatures, particularly around 4°C, significantly slow the larval development of Anguillicoloides crassus, with third-stage larvae surviving but unable to invade the swimbladder wall at this temperature(Knopf et al. 1998) In intermediate hosts such as copepods, no larval development occurs at 4–6°C, even after extended periods, while development to the infective third stage is much faster at higher temperatures (e.g., 6 days at 28°C versus 31 days at 12–14°C(Bonneau et al. 1991)

Adult A. crassus worms experience increased mortality, reduced growth, and diminished reproductive capacity when maintained at 4°C compared to those at warmer temperatures, indicating that cold conditions are detrimental to adult survival and fitness. These findings support the hypothesis that the spread and establishment of A. crassus in colder, boreal regions are limited by ambient temperature regimes(Knopf et al. 1998) Additionally, hatching and activity of second-stage larvae are also temperature-dependent, with hatching only occurring between 10 and 30°C and incubation time decreasing as temperature increases (Thomas et Ollevier 1993) Overall, low temperatures act as a strong constraint on the life cycle progression, survival, and reproductive success of A. crassus in both its larval and adult stages(Bonneau et al. 1991; Thomas et Ollevier 1993; 1993)

Temperature is a primary driver of temporal variations in Anguillicoloides crassus infection dynamics, as it directly influences larval development both in water and within intermediate hosts such as copepods. Experimental studies show that larval development is significantly accelerated at higher temperatures (e.g., third-stage larvae appear in 6 days at 28°C, 9 days at 21°C, and 31 days at 12–14°C), while no development occurs at 4–6°C, even after extended periods(Bonneau et al. 1991) . In the final host, the European eel, low temperatures (4°C) retard larval development and severely harm adult worms, increasing mortality and reducing growth and reproduction, whereas higher temperatures support normal parasite development(Knopf et al. 1998) Eel physiology and feeding behavior are also temperature-dependent, with main feeding activity—and thus exposure to infective larvae—occurring between April and September, peaking from April to June. Infection rates decline during periods when eels stop feeding, specifically in winter (below 10°C) and in summer (above 30°C), limiting their exposure to the parasite (Knopf et al. 1998) . Additionally, temperature affects the expression of genes related to growth, stress, and immunity in eel larvae, with optimal development and

lowest deformity rates observed at around 18°C, while both colder and warmer extremes increase deformities and stress responses (Miest et al. 2019; Politis et al. 2017)

The Swim Bladder Degenerative Index (SDI), as defined by Lefebvre et al., is a macroscopic scoring system ranging from 0 to 6 that assesses the health of the eel swim bladder based on three criteria: transparency, presence of pigmentation/debris, and wall thickness. This index is widely used to evaluate the severity of damage caused by the parasitic nematode Anguillicola crassus, which can lead to significant anatomical and physiological dysfunction in eels, sometimes independent of the current number of parasites present (Lefebvre et al. 2002). Studies show that the SDI is a valuable tool for capturing both current and past infestations, as severe bladder degeneration can persist even after parasite numbers decline, and it often correlates with reduced eel health and potential impacts on migration and reproduction (Mardja et al. 2017; Lefebvre et al. 2002) .

Research across various regions demonstrates that high SDI scores are common in heavily infested populations, with some studies repo rting over 90% of eels showing pathological signs of infection .The relationship between parasite abundance and swim bladder damage is not always linear; severely damaged bladders may contain few or no live nematodes, highlighting the importance of SDI over simple parasite counts (Lefebvre et al. 2002; Pereira et al. 2022)

The SDI has become a standard epidemiological measure in anguillicolosis studies, providing critical insights into the long-term health and population dynamics of both European and American eels(Zimmerman et Welsh 2012; Lefebvre et al. 2002)

The life cycle of Anguillicola crassus begins when eggs hatch into first-stage larvae (L1) inside the eel's swim bladder, which are then expelled into the water via the digestive tract. These larvae are ingested by small crustaceans such as copepods, which serve as intermediate hosts, where the larvae develop into the infective third-stage (L3) (Charleroy et al. 1990; Kirk 2003). Eels become infected by eating these crustaceans or paratenic hosts like small fish, insect larvae, or amphibians that have consumed infected copepods(Charleroy et al. 1990; Kirk 2003; Emde et al. 2014). Once inside the eel, L3 larvae penetrate the intestinal wall and migrate directly to the swim bladder, where they mature through L4 and pre-adult stages to become adults (Haenen et al. 1991; Charleroy et al. 1990).

The presence and development of A. crassus in the swim bladder cause inflammation, thickening, and degeneration of the bladder wall, leading to impaired function and, in severe cases, long-term anatomical and physiological damage (Haenen et al. 1991; Kirk 2003). The entire life cycle can be completed in as little as 2–3 months under favorable conditions, but may take up to a year depending on environmental factors (Charleroy et al. 1990; Haenen et al. 1991). This cycle and the resulting pathology explain how repeated or chronic infections can lead to the severe swim bladder degeneration observed in infested eel populations(Haenen et al. 1991; Kirk 2003)

All eels collected from the sampled sites exhibited pathological alterations of the swim bladder, with individuals from Lake Tonga showing the most severe lesions, followed by those from Wadi El-Kebir. The results obtained in the present study are consistent with the findings of (Neto et al. 2014) in Portuguese brackish systems, where 67% of the examined swim bladders were found to be damaged (SDI = 1.31 ± 1.23). Even more pronounced lesions were reported in French lagoons, where 92% of eels displayed pathological signs of infection, and severely affected swim bladders contained only a few living nematodes (Lefebvre et al., 2002).

Assessment of the Swim Bladder Degeneration Index (SDI) in European eels consistently reveals high rates of swim bladder damage across various regions, with studies reporting 92–95% of eels exhibiting pathological alterations and SDI values ranging from 1 to 5 (Tahri et al. 2016) These findings align with earlier European research, which documented damage rates of 71–95% when both current and past infections were considered, and showed that severe lesions can persist even when only a minority of eels harbor adult nematodes . The high prevalence of damage is attributed to repeated or chronic infestations by Anguillicoloides crassus, which cause cumulative pathological effects such as wall thickening, inflammation, fibrosis, and nodule formation, often resulting in compromised swim bladder function (Tahri et al. 2016; Lefebvre et al. 2002)

Histopathological changes include thickening of the swim bladder wall, inflammation, hyperplasia, fibrosis, and epithelial cell alterations, all of which compromise swim bladder function and may impair migration and reproductive succes(Würtz et Taraschewski 2000)

The severity and prevalence of these lesions can vary by habitat, with eels from certain lakes or inner coastal waters showing higher rates of infection and damage compared to those from more saline or open habitats(Simon et al. 2023) The Swim Bladder Degenerative Index (SDI)

remains a valuable tool for quantifying the extent of pathological changes and monitoring the health status of eel populations across different regions(Tahri et al. 2016; Mardja et al. 2017)

Macroscopic alterations typically appear after repeated infections, and some eels with adult parasites may still have undamaged bladders, suggesting that host–parasite dynamics, density-dependent regulation, and possible immune adaptation play roles in infection stabilization (Lefebvre et al. 2002) Pathological changes are observed across all life stages, including glass eels, and can trigger stress responses, increased spleen mass, and reduced oxygen concentration in the swim bladder, impairing buoyancy and migration capacity (Tahri et al. 2016)

Visible pathological alterations in the swim bladder of Anguilla anguilla resulting from Anguillicoloides crassus infection have been comprehensively described by Lefebvre et al. (2002b). These include marked thickening of the swim bladder wall due to acute inflammation and fibrotic processes. The L3 and L4 larval stages are typically embedded within the bladder wall, inducing nodule formation, whereas adult nematodes, which are haematophagous, inhabit the lumen of the organ and trigger host immune defense reactions. Collectively, these alterations contribute to the establishment of a host–parasite equilibrium, wherein the swim bladder remains structurally and functionally compromised but not completely destroyed, permitting the persistence of both the host and the parasite (Würtz & Taraschewski, 2000; Dezfuli et al., 2021).

In **glass eels (civelles)** and **juvenile eels**, histopathological analyses have revealed **pronounced structural and cellular alterations** of the swim bladder, characterized by **wall thickening, inflammatory infiltration, fibrosis**, and **epithelial hyperplasia with cellular proliferation**—hallmarks of severe tissue remodeling induced by *Anguillicoloides crassus* infection (Würtz & Taraschewski, 2000; Dezfuli et al., 2021). These lesions are accompanied by **intense immune cell infiltration**, particularly **granulocytes and monocytes**, surrounding the parasite larvae, indicating an **active host inflammatory and defense response** (Knopf et al., 2008).

Experimental studies further demonstrate that *A. crassus* infection elicits a **strong physiological stress response**, evidenced by **elevated cortisol levels**. This endocrine stress is **exacerbated under adverse environmental conditions**, such as hypoxia, low oxygen concentration, or pollution. Under hypoxic exposure, infected eels exhibit **significantly higher**

corticosteroid (cortisol) responses and **increased metabolic costs** compared to uninfected counterparts (Gollock et al., 2005).

A **strong negative correlation** exists between **swim bladder oxygen concentration** and **parasite load**, with oxygen levels reported to decline from approximately **65% to 11%** as infection intensity increases (Blanc, 1998; Pelster, 2023; Palstra et al., 2007; Würtz et al., 1996). This sharp reduction in oxygen impairs the **buoyancy-regulating capacity** of the swim bladder, forcing eels to **expend greater muscular energy** to maintain vertical position—particularly critical during their **long-distance spawning migration to the Sargasso Sea**.

Although early studies suggested minimal impact of *A. crassus* on **osmoregulation** and **pressure acclimation** in silver eels (Fontaine et al., 1990), more recent research has consistently demonstrated that **both lightly and heavily infested eels experience reduced swimming performance and endurance**, with **severely affected individuals unable to complete simulated migratory trials** (Palstra et al., 2007; Pelster, 2023).

Moreover, eels with **damaged or degenerated swim bladders** are markedly **more susceptible to environmental stressors**, especially **hypoxia during warm summer months**, leading to **increased mortality** in severely affected individuals (Kirk, 2003; Palstra et al., 2007; Würtz et al., 1996). Histological impairments—such as **fibrosis, inflammation, and loss of gas gland function**—further compromise the swim bladder's ability to regulate **oxygen and buoyancy** (Pelster, 2023; Würtz et al., 1996).

In summary, infection by *Anguillicoloides crassus* profoundly disrupts the **physiology and functionality** of the eel swim bladder, leading to **impaired buoyancy control, increased metabolic stress, reduced endurance**, and **greater vulnerability to environmental pressures**. Collectively, these pathological and physiological effects contribute to **reduced survival and migratory success**, posing a significant threat to the **reproductive potential and population recovery** of the European eel (*Anguilla anguilla*).

Conclusion

The analysis of European eel (*Anguilla anguilla*) populations from Lake Tonga and Wadi El-Kebir highlights distinct yet complementary demographic and biological patterns consistent with those observed across North African and European habitats.

The dominance of intermediate size classes (400–500 mm; 200–400 g) in both sites, particularly in Lake Tonga, indicates a healthy representation of yellow eels in active growth phases.

Seasonal variations in body condition—characterized by higher weights during spring and autumn and reduced values in winter. The predominance of immature or early maturing stages (I–FII) and the limited occurrence of fully mature silver eels suggest that both sites function mainly as **growth habitats** where eels undergo somatic development before initiating the migratory phase (EELREP, 2005).

A marked female-biased sex ratio (3.3:1 in Lake Tonga; 2:1 in Wadi El-Kebir) confirms the influence of environmental factors—such as habitat type, food availability, and population density—on sex differentiation, favoring female development in low-density, high-growth environments like lakes and large rivers (Geffroy & Bardonnet, 2016; Tahri & Panfili, 2023).

Morphometric indicators, particularly the **ocular index (OI)** and **pectoral fin index (PFI)**, proved effective in assessing silvering status. The high proportion of silver eels in Lake Tonga (85%) compared to Wadi El-Kebir (60%) underscores spatial variability in migratory readiness, likely driven by local ecological conditions and population density

Eels from Lake Tonga exhibited negative allometric growth (b = 2.83), indicating a tendency toward elongation as length increases, while those from Wadi El-Kebir displayed nearly isometric growth (b = 2.95), reflecting proportional body development.

The Gonadosomatic Index (GSI) showed a positive correlation with total length and Ocular Index (OI) at both sites, confirming that larger and more silvered eels exhibit more advanced gonadal maturation. Seasonal fluctuations in GSI, Hepatosomatic Index (HSI), and Empty Gut–Somatic Index (EGSI) revealed synchronized physiological changes associated with the

silvering process and migration readiness, with highest values generally observed in spring and winter.

Growth coefficient (k) and condition factor (K) both varied seasonally, peaking in spring and autumn, consistent with enhanced feeding and metabolic activity during these periods.

Feeding activity of *Anguilla anguilla* varied by site, season, and size. Eels from Lake Tonga showed higher feeding intensity (CV ≈51%) than those from Wadi El-Kebir (≈68%), with activity peaking in summer and spring. Smaller eels fed actively, while larger, silvering individuals showed reduced feeding. Diet composition revealed piscivory dominance at Lake Tonga (36% fish) and a more diversified, crustacean-rich diet at Wadi El-Kebir (29%), confirming strong trophic plasticity and adaptation to local environmental conditions.

Age determination of *Anguilla anguilla* from Lake Tonga and Wadi El-Kebir confirmed that both populations are dominated by young and intermediate individuals (1–4 years), with a mean age of about 3 years,

The parasitic fauna of *Anguilla anguilla* from Lake Tonga and Wadi El-Kebir revealed six taxa, dominated by *Pseudodactylogyrus sp.*, followed by *Ergasilus gibbus*, *Argulus sp.*, *Bothriocephalus claviceps*, *Hysterothylacium sp.*, and *Anguillicoloides crassus*.

Pseudodactylogyrus sp. exhibited the highest prevalence (>60%) and intensity, with infection peaks occurring in winter, confirming its dominance in gill parasitism, as reported in other Mediterranean populations.

Seasonal and size-related variations reflect environmental effects and host behavior. High SDI values indicate persistent swim bladder damage, showing chronic impairment. Overall, *A. crassus* infection severely affects eel health and migration, contributing to the decline of *A. anguilla* populations.

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