SOUTHERN INDIAN OCEAN FISHERIES AGREEMENT

Assessment of SIOFA Species and Ecosystems for Vulnerability to Climate Change Impacts

Contract CLI-2025-01

ANNEX 3

Literature Review

Oilfish / (Ruvettus pretiosus)

Introduction

This literature review evaluates all seven climate hazard indicators (H1–H7) and ten biological and ecological sensitivity and adaptive capacity indicators (S1–S10) for oilfish (*Ruvettus pretiosus*) in the SIOFA Area. Note that SIOFA catch records aggregate oilfish with escolar (*Lepidocybium flavobrunneum*); this assessment addresses *R. pretiosus* specifically.

The review is structured in two parts. Part 1 works through the hazard indicators. For each hazard, the assessment first establishes what is occurring in the Indian Ocean — drawing primarily on the Indian Ocean Climate Summary (Kryc 2026 - Attachment F) — and then evaluates exposure across three dimensions: oilfish as a species (direct physiological and behavioural impacts); mesopelagic and deep-water habitat characteristics (physical and structural changes to the environment the species occupies, including oxygen minimum zone dynamics); and food web and prey availability (indirect effects operating through the trophic pathways that sustain oilfish). The purpose is to identify which hazards are materially relevant and through what pathways.

Part 2 evaluates the biological and behavioural characteristics that determine how oilfish would respond to those hazards. Sensitivity indicators address the magnitude of likely response — how strongly a given hazard affects the species given its intrinsic biology, including physiological tolerances, life history strategies, mobility, reproductive strategies, dietary flexibility, and competitive interactions. Adaptive capacity indicators address the scope for adjustment — whether the species has the biological flexibility or ecological options to reduce adverse outcomes. Some indicators appear in both parts: thermal range and prey specificity, for example, are relevant to exposure in Part 1 and to response capacity in Part 2. They are asking different questions in each context, and the ratings should be interpreted accordingly.

Table of Contents

Baseline Characterisation: Oilfish Biology, Habitat, and Food Web

Oilfish as a Species: Biological Characteristics

Oilfish (*Ruvettus pretiosus*) is the largest species within the family Gempylidae, a group of snake mackerels distributed globally in temperate and tropical waters (Nakamura & Parin, 1993). Within SIOFA fisheries data, oilfish is aggregated with escolar (*Lepidocybium flavobrunneum*), as both are benthopelagic gempylids caught using similar fishing methods, primarily longlines. This assessment focuses on *R. pretiosus* while acknowledging that SIOFA catch statistics (averaging 13,530 tonnes annually during 2018-2022) combine both species.

Oilfish can attain impressive dimensions, reaching maximum recorded lengths exceeding 2 metres and weights of 63.5 kg, though specimens of this size are uncommon (Australian Museum, 2021.). Within the SIOFA Area, average weights of landed oilfish are approximately 27 kg, considerably smaller than maximum reported sizes. The species exhibits a distinctive biological characteristic that shapes its ecology and commercial value: exceptionally high concentrations of wax esters (primarily cetyl oleate and oleyl oleate) throughout its tissues. Cox and Reid (1932) demonstrated that oilfish oil consists of roughly equal proportions of saponifiable and unsaponifiable constituents, with minimal glycerol content, indicating the lipids exist primarily as wax esters rather than triglycerides typical of most fish oils. These indigestible wax esters confer purgative properties when consumed in quantity, leading to sales bans in countries including Japan and Italy despite the species' commercial appeal in other markets.

Reproductive biology of oilfish remains poorly documented globally, with limited information available from any ocean basin. Vasilakopoulos et al. (2011), examining specimens from the eastern Mediterranean, provided the most comprehensive reproductive data to date. Their histological analysis revealed oilfish as a gonochoristic species (separate sexes with no hermaphroditism) exhibiting multiple spawning with either asynchronous or group-synchronous oocyte development patterns. Spawning appears to occur during mid to late summer in Mediterranean populations, though the authors noted an inability to collect specimens during peak spawning months. Notably, oilfish produce relatively small pelagic eggs (approximately 1 mm diameter at spawning) compared to other large pelagic and benthopelagic species—a characteristic the authors suggest may facilitate rapid dispersal and movement of eggs and larvae to surface waters, though this hypothesis requires testing.

For the Indian Ocean and SIOFA region specifically, spawning seasonality, spawning locations, and fecundity remain completely unknown. Similarly, fundamental life history parameters including age at maturity, maximum age, and growth rates have not been determined for any population. Observer programmes have collected 21,192 weight samples from oilfish in the SIOFA Area, yet these data are not unanalysed for size frequency distributions or growth patterns. The absence of ageing studies—typically conducted using otoliths, vertebrae, or other hard structures—is a critical knowledge gap limiting population assessment capacity.

Habitat Characteristics

Oilfish exhibits a circumglobal distribution spanning tropical and temperate waters between approximately 55°N and 43°S across all major ocean basins (Australian Museum, 2021.; Animalia.bio). The species occupies a benthopelagic ecological niche, closely associated with seafloor topography rather than existing purely in the water column. Its vertical distribution ranges from 100 metres to 975 metres depth, with most populations concentrated between 200-400 metres—positioning oilfish in the upper mesopelagic to lower epipelagic zones (Chinese Taipei SIOFA National Report, 2020).

Within this depth range, oilfish demonstrates clear habitat preferences for specific topographic features. The species concentrates over continental slopes and seamounts, geological structures that generate localised oceanographic conditions including current acceleration, vertical mixing, and enhanced productivity. These associations mirror patterns observed in other commercially important deep-water species including alfonsino (*Beryx splendens*) and orange roughy (*Hoplostethus atlanticus*), with which oilfish frequently co-occurs in fisheries catches.

In the SIOFA Area specifically, oilfish distribution is not uniform but instead concentrated in western regions, particularly within Subareas 1 and 3b (SIOFA, 2025). This spatial concentration may reflect underlying habitat availability (seamount and slope density), oceanographic conditions (productivity, temperature, currents), or fishing effort distribution—these alternatives cannot currently be distinguished. Behavioural observations indicate oilfish occur solitarily or in pairs rather than forming large aggregations, contrasting with schooling behaviours exhibited by many pelagic species. The

species is described as oceanodromous, undertaking movements across oceanic regions, though the scale, frequency, and drivers of these movements remain undocumented.

A fundamental knowledge gap concerns stock structure and connectivity between subareas within the SIOFA region. Whether oilfish populations in different subareas constitute genetically distinct stocks, behaviourally isolated populations, or well-connected subpopulations of a single stock remains unknown. This uncertainty has direct implications for fisheries management: if populations are isolated, localised depletion could occur without recolonisation from adjacent areas, whereas connected populations might demonstrate greater resilience to spatially-focused fishing pressure. Similarly, movement patterns between depth zones remain poorly characterised beyond the diel vertical migrations documented for portions of the population (discussed in Food Web and Trophic Ecology, below).

Food Web and Trophic Ecology

Oilfish functions as a high-level predator within deep-water marine ecosystems, occupying trophic level 4.0-4.5 (Chinese Taipei SIOFA National Report, 2020; Animalia.bio). This position indicates the species consumes prey that are themselves predators (secondary and tertiary consumers), placing oilfish near the apex of mesopelagic and benthopelagic food webs. The species exhibits a generalist predatory strategy, consuming diverse prey types rather than specialising on particular species or taxa.

Vasilakopoulos et al. (2011) conducted the most comprehensive dietary analysis of oilfish to date, examining stomach contents from 30 specimens in the eastern Mediterranean with intact digestive tracts. Their results revealed teleost fishes as the most numerically abundant and frequently occurring prey (61.9% numerical abundance, 60% occurrence frequency), followed by cephalopods (28.6% numerical abundance, 33.3% occurrence). Identified prey species included hake (*Merluccius merluccius*), silver scabbardfish (*Lepidopus caudatus*), European conger (*Conger conger*), macrourid species, and squid of the genus *Todarodes*. Additional sources note consumption of crustaceans (Australian Museum, 2021.; Animalia.bio), though these appeared less frequently in the Mediterranean study. This prey spectrum—benthopelagic and mesopelagic fishes, cephalopods, and crustaceans—characterises oilfish as a generalist predator of the mesopelagic community.

A behavioural characteristic critical to understanding oilfish ecology is diel vertical migration, though importantly this behaviour does not characterise the entire population. Portions of oilfish populations undertake nocturnal vertical migrations from benthopelagic daytime habitats (200-975m depth) to epipelagic waters near the surface for feeding after sunset (Chinese Taipei SIOFA National Report, 2020; Te Papa Museum, 2023). This migration pattern enables access to epipelagic prey communities unavailable in deeper waters. However, as Vasilakopoulos et al. (2011) documented, not all individuals perform these energetically demanding vertical movements—some remain in benthopelagic zones throughout the diel cycle, presumably feeding on benthic and near-bottom prey when available.

This partial migration strategy demonstrates behavioural flexibility, with Vasilakopoulos et al. (2011) proposing that individuals may facultatively adopt different foraging strategies depending on benthic prey availability and energetic status. Their observation that all specimens caught by surface longlines (operating 10-20m depth at night during vertical migration periods) had empty stomachs, while only 52% of specimens caught by demersal longlines (250-550m depth) had empty stomachs, provides indirect support for this hypothesis. The high overall frequency of empty stomachs (63.3% in their study) may reflect the species' less active mode of life and substantial stored energy reserves in the form of wax esters, potentially reducing the necessity for constant feeding relative to more metabolically active pelagic predators.

Critically, diet composition of oilfish in the Indian Ocean remains entirely undocumented—no published stomach content analyses exist from this region. Whether dietary patterns observed in the Mediterranean generalise to Indian Ocean populations, or whether regional differences in prey communities drive divergent dietary specialisations, cannot currently be determined. Similarly, environmental triggers for vertical migration, prey selection mechanisms, seasonal dietary shifts, and ontogenetic changes in diet composition all remain unstudied. Given that prey communities represent the mechanistic link between ocean productivity and oilfish population dynamics, the absence of regional dietary data represents a significant constraint on understanding how environmental changes (productivity declines, warming-driven prey distribution shifts, oxygen minimum zone expansion affecting mesopelagic communities) may impact oilfish populations in the SIOFA Area.

PART 1: HAZARD ASSESSMENT (H1-H7)

For each of the seven climate hazard indicators, this section establishes the documented and projected change in the Indian Ocean (drawn primarily from the IO Climate Summary, Attachment F) and then evaluates exposure across three dimensions: oilfish as a species, the mesopelagic and deep-water habitats it occupies, and the food web that sustains it. The purpose is to identify which hazards are materially relevant to oilfish and through what pathways — the foundation on which the sensitivity assessment in Part 2 is built.

H1: Marine Heatwaves

What Information IS Available:

Marine heatwave (MHW) frequency in the Indian Ocean has doubled over recent decades, as documented in the IO Climate Summary (2026) — a synthesis drawing on rapid climate change analyses across the region. This doubling of MHW frequency represents a substantive change in the thermal regime experienced by species inhabiting these waters, with implications for all temperature-sensitive biological processes including metabolism, growth, reproduction, and survival.

Oilfish occupies a benthopelagic ecological niche with core depth distribution between 200-400 metres, positioning the species in the upper mesopelagic zone. This depth range provides partial thermal buffering against surface temperature anomalies, as heat penetrates downward from the ocean surface with attenuation—surface warming of several degrees may translate to sub-degree changes at 200-400m depth, depending on stratification strength and mixing dynamics. Azarian et al. (2023) demonstrated that marine heatwaves in the southern Indian Ocean penetrate to depths of 500 metres, indicating that oilfish depth range does not provide complete thermal refuge, though the magnitude of temperature change at depth is reduced compared to surface layers.

However, this depth-related buffering is partially offset by the species' behavioural ecology. As documented in the Food Web and Trophic Ecology section, portions of oilfish populations undertake diel vertical migrations, ascending from benthopelagic daytime habitats (200-975m depth) to epipelagic waters near the surface (10-20m depth) for nocturnal feeding. During these vertical migrations, oilfish are directly exposed to surface thermal conditions, including marine heatwave anomalies. The duration and frequency of surface exposure depends on feeding success and energetic requirements—variables that remain unstudied but likely vary among individuals and with environmental conditions.

The species' biogeographic distribution provides indirect evidence regarding thermal tolerance breadth. Oilfish exhibits a cosmopolitan distribution spanning tropical and temperate waters between approximately 55°N and 43°S across all major ocean basins (Atlantic, Pacific, Indian). This broad latitudinal range necessarily encompasses substantial thermal variation—tropical populations experience consistently warm temperatures (25-30°C at surface), while temperate populations at higher latitudes experience seasonal temperature ranges potentially spanning 10-25°C. The species' ability to persist across this thermal gradient implies physiological tolerance mechanisms enabling function across a relatively wide temperature range, though the actual thermal tolerance limits remain unmeasured.

While not based on direct physiological measurements, this assessment suggests oilfish possesses characteristics conferring moderate inherent resilience to environmental change relative to other species.

What Information IS NOT Available:

The most critical knowledge gap concerns the complete absence of empirical thermal physiology data for oilfish. No laboratory studies have determined thermal tolerance limits for the species—neither critical thermal maximum (CTmax, the temperature causing loss of equilibrium and imminent mortality) nor critical thermal minimum (CTmin) have been measured. These fundamental parameters define the species' thermal niche boundaries and are essential for predicting vulnerability to warming. Without CTmax data, we cannot determine how close current or projected temperatures are to lethal limits, nor can we assess safety margins against marine heatwave extremes.

While broad distributions often correlate with broad tolerance ranges, this relationship is not invariable—some widely distributed species comprise multiple locally adapted

populations with restricted individual tolerances rather than single populations with broad plasticity. Whether oilfish populations across its range represent a single broadly tolerant lineage, multiple thermally adapted populations, or cryptic species with restricted tolerances cannot be determined from distributional data alone.

Behavioural responses to thermal stress remain completely unknown. When oilfish encounter marine heatwave conditions during nocturnal vertical migrations, do they: (1) curtail or cease vertical migrations, remaining at depth to avoid thermal stress (potentially reducing feeding success and condition), (2) continue migrations despite thermal stress, experiencing sublethal effects on metabolism, immune function, or reproductive capacity, or (3) tolerate surface heatwave conditions without measurable impacts due to broad thermal tolerance? Each response scenario has different implications for population persistence, yet we have no basis for predicting which would occur.

Thermal acclimation capacity—the ability to adjust physiological performance in response to sustained temperature changes—has not been assessed. Some fish species demonstrate substantial acclimation capacity, shifting thermal tolerance limits upward following exposure to elevated temperatures over days to weeks. Other species exhibit limited acclimation, remaining vulnerable to warming despite acclimatisation opportunities. Whether oilfish can physiologically compensate for gradual ocean warming through acclimation, or whether populations are constrained by fixed thermal limits, fundamentally affects climate vulnerability but remains unknown.

No information exists regarding thermal effects on critical life processes. Temperature strongly influences fish reproduction, embryonic development, larval growth, and juvenile survival, yet we lack data on: optimal temperature ranges for spawning success, thermal tolerance windows for eggs and larvae (typically narrower than adult tolerance), temperature effects on growth rates, or thermal influences on prey capture efficiency and foraging success. Early life stages are frequently more thermally sensitive than adults, potentially creating population bottlenecks even if adult thermal tolerance is adequate.

Similarly absent are data on interactive effects between temperature and other stressors. Marine heatwaves often coincide with deoxygenation events as warming reduces oxygen solubility and stratification limits vertical mixing. The combined effects of elevated temperature and reduced oxygen may be synergistic rather than additive—thermal stress increases metabolic oxygen demand while oxygen availability declines. Oilfish vulnerability to this interaction cannot be assessed without physiological data on both thermal and oxygen tolerance.

Synthesis and Rating Justification

MEDIUM — The hazard itself (Indian Ocean marine heatwave frequency doubling) is well-documented through robust oceanographic monitoring and analysis. Multiple independent studies confirm rapid warming and increased heatwave frequency and intensity across the Indian Ocean basin (IO Climate Summary, 2026). However, species-specific physiological responses remain entirely unknown, creating a fundamental evidence gap between documented hazard exposure and predicted biological consequences.

This rating reflects competing factors that partially offset each other:

Factors reducing exposure and vulnerability:

The species' benthopelagic depth distribution (core habitat 200-400m) provides meaningful thermal buffering compared to obligate surface-dwelling species. Temperature anomalies attenuate with depth—a 3°C surface marine heatwave may manifest as a 0.5-1°C anomaly at 300m depth, substantially reducing thermal stress magnitude. This depth buffering represents a genuine protective mechanism not available to epipelagic species.

The cosmopolitan distribution spanning 55°N to 43°S implies the species has evolved mechanisms to tolerate substantial thermal variation. Populations persisting in both tropical (warm, thermally stable) and temperate (cooler, seasonally variable) regions suggests physiological flexibility or local adaptation enabling function across approximately 10-15°C temperature range at minimum.

Factors increasing exposure and vulnerability:

Diel vertical migration behaviour creates direct exposure to surface thermal anomalies that depth distribution would otherwise avoid. During nocturnal ascents to 10-20m depth for feeding, migrating individuals experience the full magnitude of surface marine heatwave conditions. The duration and frequency of this exposure depends on foraging requirements and success—factors that vary among individuals and remain unstudied—but necessarily creates thermal stress episodes absent in non-migrating deep-dwelling species.

The critical uncertainty regarding thermal tolerance limits prevents assessment of safety margins. If oilfish CTmax approaches temperatures currently experienced during marine heatwaves (30-32°C in tropical Indian Ocean), the species would be highly vulnerable to thermal stress despite depth buffering. Conversely, if CTmax substantially exceeds current extremes (e.g., 35-37°C), the species could tolerate projected warming with minimal impacts. The inability to distinguish between these scenarios fundamentally limits risk assessment confidence.

The absence of data on behavioural responses introduces additional uncertainty. If thermal stress causes oilfish to curtail vertical migrations, the species may avoid direct thermal mortality but experience indirect consequences through reduced feeding success, declining body condition, or impaired reproduction. These sublethal effects could cause population declines without direct temperature-induced mortality, yet remain completely unquantifiable without empirical studies.

The MEDIUM rating acknowledges that benthopelagic habitat provides genuine buffering against surface warming—this is not a highly exposed surface species—but vertical migration behaviour and unmeasured tolerance limits create meaningful uncertainty. The species likely occupies an intermediate position on the vulnerability spectrum: less vulnerable than obligate epipelagic species experiencing full surface thermal extremes, but potentially more vulnerable than non-migrating deep-water species completely avoiding surface conditions.

H2: Increased Sea Surface Temperature

What Information IS Available

The Indian Ocean has experienced sustained baseline warming of 1.2°C since 1950, representing the fastest warming rate of any ocean basin except the Arctic (Dalpadado et al., 2023). This chronic, directional temperature increase represents a fundamentally different hazard from the marine heatwave events discussed in H1.

Marine heatwaves (H1) impose episodic, acute thermal stress—discrete extreme events lasting days to weeks that then subside. In contrast, increased sea surface temperature (H2) represents a permanent shift in baseline thermal conditions that persists across decades, creating sustained physiological demands for acclimation, adaptation, or distributional shifts. Species must either adjust their physiology to maintain performance at the new thermal baseline, relocate to track historical thermal conditions, or experience chronic suboptimal performance in degraded habitat.

The 0.17°C per decade average warming rate (calculated from the 1.2°C total over seven decades) may appear gradual, but this rate exceeds the adaptive capacity documented for many marine ectotherms. Unlike the rapid but temporary temperature spike of a marine heatwave—which organisms may survive through short-term behavioural avoidance or stress tolerance—chronic baseline warming requires sustained physiological adjustment or evolutionary adaptation across multiple generations. The cumulative nature of this change means each successive generation experiences thermal conditions further removed from those under which the population evolved.

Critically for benthopelagic species like oilfish, warming penetrates beyond surface layers. Wenegrat et al. (2020) documented subsurface warming rates of 0.04°C per decade at 750 metres depth in the Indian Ocean. While this subsurface warming rate is substantially attenuated compared to surface rates (approximately 25% of surface magnitude), it demonstrates that the depth range oilfish occupies (100-975m, typically 200-400m) is experiencing measurable and sustained temperature increases. The benthopelagic habitat does not provide thermal refuge from chronic warming—it attenuates warming magnitude but does not eliminate baseline thermal change. Over the seven decades since 1950, this translates to approximately 0.3°C warming at oilfish core depths (200-400m), compared to 1.2°C at the surface.

The vertical structure of Indian Ocean warming has important implications for depth-distributed species. Azarian et al. (2023) demonstrated that warming penetrates to 500 metres depth in the southern Indian Ocean, encompassing the full core depth range of oilfish populations. The upper mesopelagic zone (200-1000m) is therefore experiencing sustained baseline warming that affects all aspects of benthopelagic ecology: habitat thermal conditions, metabolic rates, prey community composition and distribution, and reproductive processes.

A further structural change intensifies the thermal environment oilfish encounter during diel migrations. The IO Climate Summary (2026) documents progressive shoaling of the Indian Ocean thermocline under continued warming — the thermal boundary between

surface mixed layer and cooler deep water is rising. For a species that migrates nightly from 200–400m to 10–20m, thermocline shoaling has a compounding effect: it steepens the temperature gradient the animal crosses during ascent and descent, and it may compress the cooler intermediate water that oilfish can retreat to during daytime. If the thermocline shoals sufficiently, the thermal refuge available to benthopelagic species at depth could narrow even without an equivalent increase in deep-water temperatures. This shoaling dynamic is distinct from the surface and subsurface warming trends discussed above and represents an additional thermal hazard pathway specific to vertically migrating species.

As discussed in H1, oilfish behavioural ecology further complicates thermal exposure patterns. Portions of the population undertake diel vertical migrations, ascending to epipelagic waters (10-20m depth) for nocturnal feeding. During these migrations, individuals experience the full magnitude of surface warming—the complete 1.2°C baseline increase since 1950, not the attenuated 0.3°C experienced at depth. This creates a dual thermal environment: benthopelagic daytime habitat has warmed moderately (0.3°C), while epipelagic nighttime feeding habitat has warmed substantially (1.2°C). Species experiencing this pattern face sustained physiological demands in both depth zones, with the magnitude of chronic thermal stress varying by depth and time of day.

The interaction between H1 (marine heatwaves) and H2 (increased baseline SST) is additive and potentially synergistic. The 1.2°C baseline warming represents the new "normal" thermal conditions, upon which marine heatwave anomalies are superimposed. Historical marine heatwaves occurred against a cooler baseline (e.g., a +3°C heatwave in 1980 reached absolute temperatures of X°C), while contemporary marine heatwaves occur against a 1.2°C warmer baseline (the same +3°C heatwave anomaly in 2025 reaches X+1.2°C absolute temperature). This means both chronic thermal stress (H2) and acute thermal extremes (H1) are simultaneously increasing, with cumulative impacts potentially exceeding either stressor in isolation.

The species' broad biogeographic distribution (55°N to 43°S, circumglobal) provides indirect evidence regarding thermal tolerance breadth. Oilfish populations persisting across tropical (consistently warm) and temperate (seasonally variable, cooler) regions necessarily experience a wide range of baseline thermal conditions. Current tropical populations exist at baseline temperatures (surface: ~28-30°C, 200-400m depth: ~15-20°C) substantially warmer than temperate populations (surface: ~15-25°C seasonally, 200-400m depth: ~10-15°C). This distributional pattern suggests the species possesses physiological mechanisms enabling function across a thermal envelope spanning at minimum 10-15°C at depth, demonstrating capacity to tolerate a range of baseline thermal conditions substantially exceeding the 1.2°C increase observed since 1950.

However, this distributional evidence must be interpreted cautiously. The presence of populations across a wide thermal range does not necessarily indicate that individual populations can tolerate shifting baselines. The observed pattern could reflect: (1) a single broadly tolerant lineage with wide thermal performance curves—in which case populations could tolerate the 1.2°C baseline shift, or (2) multiple locally adapted populations with narrower individual tolerances collectively occupying a wide thermal

range—in which case each population might be vulnerable to local baseline warming despite the species' overall broad distribution. Genetic or physiological studies would be required to distinguish these scenarios.

What Information IS NOT Available:

The most fundamental knowledge gap concerns the complete absence of data on oilfish preferred temperature range and thermal performance curves. While distributional data indicates the species tolerates a wide range of temperatures (inferred from the 55°N-43°S latitudinal span), we do not know: (1) what temperature range supports optimal physiological performance (growth, reproduction, foraging efficiency, immune function), (2) what temperature ranges represent suboptimal habitat where populations persist but with reduced fitness, or (3) how thermal performance degrades as temperatures move away from the optimum. Without defining the species' thermal optimum and the shape of its thermal performance curve, we cannot assess whether the 1.2°C baseline warming since 1950 has maintained populations within optimal thermal conditions, shifted them into suboptimal ranges, or pushed them toward physiological tolerance limits.

This uncertainty manifests differently across the species' range. The same 1.2°C warming has fundamentally different implications for populations at different latitudes:

- **Tropical populations** currently exist at the warmest end of the species' thermal distribution. If these populations already occupy near-maximum thermal tolerance conditions, the 1.2°C warming could push them beyond thermal optima or even approach physiological limits. These populations may be experiencing chronic thermal stress, declining performance, or range contraction at low latitudes.

- **Temperate populations** exist at cooler baseline temperatures with greater thermal headroom. The 1.2°C warming could potentially improve conditions for these populations if historical temperatures were below optimal, or it could represent neutral change if warming maintains them within optimal ranges.

Without thermal performance data, we cannot determine which scenario applies, nor can we predict how continued warming will affect populations differently across latitudes.

The capacity to predict distributional shifts in response to sustained baseline warming remains completely constrained by interconnected knowledge gaps. As baseline temperatures increase, species may respond through:

1. Poleward latitudinal shifts — tracking isotherms toward cooler high-latitude waters to maintain preferred thermal conditions. Whether oilfish can exhibit this response depends on:

- Adult mobility and dispersal capacity (S2: Adult Mobility — unknown): Can populations actively relocate hundreds to thousands of kilometres poleward? What are movement rates and distances?

- Habitat availability at higher latitudes (S3: Habitat Specificity — partially known): Are suitable seamounts and continental slopes available at higher latitudes? The

species associates with topographic features—if these are limited or absent at higher latitudes, poleward expansion may be constrained regardless of mobility.

- Ecological interactions at range margins: Do resident species at higher latitudes compete with or exclude colonising oilfish? Are prey communities at higher latitudes suitable?

2. Vertical distributional shifts — moving deeper within the water column to access cooler temperatures. Feasibility depends on:

- Physiological tolerance of deeper conditions: Can oilfish tolerate increased pressure, reduced light, and potentially lower oxygen at greater depths?
- Prey availability at depth: The species' prey (benthopelagic/mesopelagic fish, cephalopods, crustaceans) may not extend to greater depths in sufficient densities to sustain populations.
- Reproductive constraints: If spawning requires specific depth ranges, or if eggs/larvae must ascend to surface layers for development, deeper adult distributions may be incompatible with reproductive requirements.

3. In situ acclimation or adaptation — remaining in current locations while physiologically adjusting to warmer baseline conditions. This response depends on:

- Physiological plasticity: Can individuals adjust thermal tolerance limits or metabolic performance to compensate for warming? Acclimation studies are completely absent.
- Evolutionary adaptive capacity: Can populations undergo genetic adaptation to warming over multiple generations? This depends on heritability of thermal tolerance traits, effective population size, and generation time—none of which are known.
- Rate of warming versus rate of adaptation: Even if adaptive capacity exists, does it operate quickly enough to track the observed 0.17°C/decade warming rate? Evolutionary adaptation typically occurs over many generations—if oilfish generation time is long (likely, given large body size), adaptation may lag warming.

Early life history stages represent a critical vulnerability to baseline warming that may differ substantially from adult responses. Dahlke et al. (2020) demonstrated through comprehensive comparative analysis across 694 fish species that early life stages (eggs, larvae, early juveniles) typically exhibit thermal tolerance windows 2-3 times narrower than conspecific adults. This pattern arises because developing organisms possess less physiological capacity for thermal compensation than fully developed adults—metabolic systems, osmoregulation, and homeostatic mechanisms are still maturing. If oilfish follows this general pattern, eggs and larvae could be sensitive to temperature changes that adults tolerate.

The implications for population persistence under baseline warming are profound. If adults can tolerate the 1.2°C warming through plasticity or distributional shifts, but eggs/larvae cannot develop successfully at the new thermal baseline, populations will experience recruitment failure—declining recruitment eventually translating to population decline as adults age and die without replacement. This demographic bottleneck could operate even while adult populations appear healthy.

However, oilfish reproductive biology and early life thermal requirements remain completely unstudied in the Indian Ocean:

- **Spawning thermal requirements unknown**: Do adults require specific temperature ranges to initiate spawning? Does gamete development depend on thermal cues?
- **Egg thermal tolerance unknown**: What temperature range permits successful embryonic development? Are eggs developing at 200-400m depth (where parents occur), or do buoyant eggs ascend to warmer surface layers?
- **Larval thermal windows unknown**: What temperature range supports larval growth, feeding, and survival?
- **Juvenile thermal requirements unknown**: Do recently settled juveniles have different thermal optima than adults?

The Vasilakopoulos et al. (2011) Mediterranean study documented spawning during mid-to-late summer (the warmest period), but whether this timing reflects: (1) thermal requirements (spawning requires warm temperatures), (2) prey availability for larvae (spawning when larval food is abundant), (3) photoperiod cues unrelated to temperature, or (4) other factors, is unknown. If spawning timing is thermally constrained, baseline warming could shift spawning phenology—potentially causing temporal mismatches with prey availability peaks or extending larvae into seasonally unsuitable thermal conditions.

Thermal acclimation capacity over decadal timescales—matching the pace of baseline warming—remains completely unassessed. Acclimation operates on timescales from hours (acute heat shock responses) to weeks (physiological remodelling) to potentially months (seasonal acclimatisation). Whether oilfish populations can continuously acclimate to track decadal warming trends (0.17°C per decade) through phenotypic plasticity, or whether adaptive limits constrain acclimation capacity, fundamentally affects vulnerability but remains untested.

Some fish species demonstrate substantial transgenerational plasticity—offspring of parents acclimated to elevated temperatures exhibit improved thermal tolerance even without genetic changes (non-genetic inheritance of thermal tolerance via epigenetic mechanisms, maternal provisioning, or developmental plasticity). Other species lack this capacity, with each generation requiring de novo acclimation to changing conditions. Whether oilfish exhibits transgenerational thermal plasticity is unknown.

The interaction between increased baseline SST (H2) and other chronic environmental changes compounds uncertainty. Baseline ocean warming drives multiple concurrent changes:

Oxygen minimum zone (OMZ) expansion: Warming reduces oxygen solubility and strengthens stratification, expanding and intensifying hypoxic zones in the Indian Ocean (IO Climate Summary, 2026). If oilfish respond to surface warming by shifting distributions deeper, they may encounter increasingly hypoxic conditions. This creates a potential physiological squeeze—thermal stress in shallow waters versus oxygen stress in deep waters—with suitable habitat compressed into a narrowing depth band. The species' tolerance to combined warming + hypoxia is completely unknown (see H6: Oxygen).

Productivity declines: The IO Climate Summary (2026) documents declining net primary production across Indian Ocean regions, driven by warming-induced stratification and weakened upwelling. Critically, the consequences do not stop at phytoplankton — zooplankton biomass is projected to decline by up to 40% across the Indian Ocean by 2100 (IO Climate Summary, 2026). This second-order impact matters acutely for oilfish: mesopelagic and benthopelagic food webs are sustained by the vertical flux of organic material from surface production, and zooplankton form a critical intermediate trophic link. A 40% reduction in zooplankton biomass would substantially reduce the prey available to the cephalopod and small fish communities that oilfish targets — potentially affecting condition, growth, and reproductive success even if oilfish itself is physiologically tolerant of warming. Reduced productivity cascades through food webs, affecting prey availability for oilfish. Can the species maintain condition and reproduction if prey biomass or quality declines? This combines chronic thermal stress with chronic nutritional stress—interactive effects that may be synergistic rather than additive.

Prey community shifts: Baseline warming causes poleward range shifts in many species, potentially altering prey community composition in oilfish habitats. If preferred prey shift distributions faster than oilfish populations can track, spatial mismatches could develop between predator and prey. The species' dietary flexibility (S9: Diet and Prey Specificity) may buffer these impacts, but limits of dietary plasticity under sustained prey community change are unknown.

Acidification co-occurrence: Baseline warming coincides with progressive ocean acidification (H3), creating combined stressors. While acidification effects on oilfish are unknown (H3), the combination of chronic thermal stress and pH change may have interactive effects exceeding either stressor alone.

Synthesis and Rating Justification

MEDIUM applicability

Regional oceanographic changes are robustly documented through comprehensive monitoring programs and climate analyses spanning decades. Multiple independent studies confirm sustained Indian Ocean warming in both surface and subsurface layers (IO Climate Summary, 2026; Wenegrat et al., 2020; Azarian et al., 2023). The magnitude (1.2°C surface,

~0.3°C at 200-400m depth), temporal trend (0.17°C per decade surface, 0.04°C per decade at depth), spatial extent (basin-wide), and persistence (sustained across seven decades) of baseline warming are established with high confidence. However, species-specific biological responses remain completely unstudied—thermal performance curves, tolerance limits, acclimation capacity, early life stage requirements, and population responses to observed warming are all unknown.

Competing factors create genuine uncertainty preventing confident LOW or HIGH assessment:

Factors reducing vulnerability:

- **Depth buffering substantial**: Core depth (200-400m) has experienced only ~0.3°C warming (25% of surface magnitude)—a 10°C thermal performance breadth species experiencing 0.3°C warming encounters only 3% of its range
- **Broad distribution implies tolerance breadth**: 55°N-43°S span encompasses >15°C baseline temperature variation; 1.2°C warming falls within range the species already occupies globally
- **Gradual pace permits compensation**: 0.17°C/decade surface (0.04°C/decade at depth) allows time for acclimation, transgenerational plasticity, or microevolutionary adaptation—unlike acute heatwave stress
- **Potential benefit to temperate populations**: If cooler populations exist below thermal optima, warming could improve performance

Factors increasing vulnerability:

- **Unknown thermal optimum position**: Cannot determine whether populations are within optimal ranges (neutral warming impact), approaching limits (negative impact), or below optima (positive impact)—tropical populations most likely near maximum tolerance
- **Vertical migration creates full exposure**: Nocturnal feeding at surface exposes individuals to complete 1.2°C warming, not attenuated 0.3°C—chronic metabolic cost during feeding
- **Early life stage bottleneck**: If eggs/larvae have 2-3× narrower thermal windows (Dahlke et al., 2020 pattern) and develop in warmed surface waters, recruitment could be declining while adults appear healthy
- **Unpredictable adaptive responses**: Cannot assess whether populations are successfully tracking (poleward shifts?), acclimating (physiological adjustment?), or declining (degraded performance?)—unknown mobility, acclimation capacity, and generation time prevent predictions

- **Interactive stressor effects**: Combined with OMZ expansion (depth squeeze), productivity declines (nutritional stress), and acidification—cumulative impacts may exceed individual stressors
- **Committed future warming**: 1.2°C observed does not represent equilibrium; additional 1-2°C projected by 2100 under moderate scenarios—total 2-3°C cumulative change

The MEDIUM rating reflects the species likely occupying intermediate exposure: less exposed than tropical surface-dwellers experiencing full warming with narrow distributions, but more exposed than non-migrating deep species completely buffered from surface changes. Depth buffering and broad distribution suggest tolerance capacity, but vertical migration behaviour, unknown thermal performance, and potential early life vulnerability prevent confident low-risk assessment. The 1.2°C warming already experienced has not caused detected population collapse (though monitoring is limited), suggesting impacts are not severe, but absence of evidence is not evidence of absence—sublethal effects or recruitment declines may be occurring undetected.

H3: Ocean Acidification

What Information IS Available:

Indian Ocean acidification — a documented and accelerating trend: The Indian Ocean is acidifying measurably and progressively. Chakraborty et al. (2024) analysed surface and subsurface pH changes from 1980 to 2019, documenting a decline of –0.014 to –0.015 pH units per decade driven primarily by anthropogenic CO_2 uptake, which accounts for 80–95% of the observed trend. Critically, acidification rates accelerated during the most recent decade (2010–2019), suggesting the pace of change is not constant. El Niño and positive Indian Ocean Dipole events enhance acidification rates during their active phases, meaning interannual variability is superimposed on the directional decline (Chakraborty et al. 2024). These pH changes are not confined to the surface: acidification propagates into intermediate and mesopelagic depths through water mass formation and subduction, affecting the full depth range oilfish occupies. The exposure is real and quantified.

Oilfish as a non-calcifying teleost: The biological significance of acidification depends heavily on the physiological characteristics of the species. Organisms that build calcium carbonate structures — molluscs, echinoderms, corals, pteropods, some crustaceans — are most directly vulnerable because falling pH reduces the saturation state of aragonite and calcite, impairing calcification and weakening or dissolving existing structures. Oilfish is a teleost fish with a bony internal skeleton, not external calcite or aragonite structures that must be actively maintained against ambient seawater chemistry. Direct calcification-related impacts are therefore unlikely to be the primary concern.

For teleosts more broadly, the physiological effects of acidification are more subtle. Elevated CO_2 (hypercapnia) can impair acid-base balance, requiring osmoregulatory compensation. Several studies in other fish species have documented disruption of

olfactory function under elevated CO_2 — reduced ability to detect chemical signals used in prey location, predator avoidance, and conspecific recognition. Other documented effects in teleosts include behavioural changes (altered lateralisation, risk assessment, and schooling behaviour), metabolic costs of ion regulation, and in some species, effects on otolith formation. However, responses are highly variable across species — some teleosts demonstrate considerable tolerance while others show marked behavioural impairment even at moderate CO_2 elevations. Where oilfish falls on this spectrum is entirely unknown.

Indirect pathway through prey: Oilfish occupies trophic level 4.0–4.5, dependent on mesopelagic prey communities including teleost fish, cephalopods, and crustaceans (Vasilakopoulos et al. 2011; Viana et al. 2012). The crustacean component of the diet — though quantitatively minor based on Atlantic and Mediterranean studies — includes organisms with calcified exoskeletons that are directly vulnerable to acidification. More broadly, the mesopelagic food web that sustains oilfish prey is structurally dependent on zooplankton, including pteropods and copepods that themselves depend on calcifying phytoplankton. The IO Climate Summary projects up to a 40% decline in Indian Ocean zooplankton biomass by 2100 under continued warming and stratification — and acidification compounds this stress for calcifying zooplankton components. If mesopelagic prey communities are structurally reorganised by acidification acting on lower trophic levels, the consequences for oilfish could be substantial even without any direct physiological effect on the fish itself.

What Information IS NOT Available:

No published study has examined the physiological, behavioural, or ecological responses of *Ruvettus pretiosus* — or any Gempylidae — to ocean acidification. This is a complete evidential gap. The specific questions that remain unanswered include: whether oilfish olfactory function is impaired under projected CO_2 concentrations (affecting prey detection and foraging efficiency); whether acid-base regulation imposes metabolic costs at projected pH levels; whether otolith formation is affected; and whether any behavioural disruption occurs at ecologically relevant CO_2 levels. None of these can be inferred from general teleost data because species-level variation in acidification sensitivity is wide and not predictable from taxonomy or body form alone.

The indirect food web pathway is equally uncharacterised for oilfish specifically. The absence of Indian Ocean diet data (see S9) means the precise identity and relative importance of oilfish prey in the SIOFA area are unknown. If crustaceans are a major dietary component in Indian Ocean populations — unlike their minor role in Mediterranean and Atlantic studies — acidification sensitivity through the food web could be substantially higher than the existing data suggest. Conversely, if Indian Ocean oilfish rely predominantly on teleost fish and cephalopods (both less directly vulnerable to acidification), the food web pathway may be less consequential. This question cannot be resolved without regional stomach content data.

Depth-specific pH projections for the SIOFA area at 200–400 m are not available at the resolution needed to quantify actual exposure. The broad basin-scale trends from Chakraborty et al. (2024) document surface and intermediate water acidification, but fine-scale projections relevant to specific seamount and slope habitats where oilfish concentrate are not resolved in existing models.

Synthesis and Rating Justification:

LOW–MEDIUM

The Indian Ocean acidification signal is robust, documented, and accelerating — exposure is real. For a non-calcifying teleost, however, the primary mechanisms of direct physiological impact are theoretically weaker than for calcifying organisms, and the general evidence base for teleost acidification responses, while variable, does not suggest a uniformly high-sensitivity taxon. The LOW–MEDIUM rating reflects this: the hazard is present and the indirect food web pathway is a genuine concern, particularly given the projected collapse in zooplankton biomass, but oilfish occupies an intermediate vulnerability position relative to calcifiers. The rating cannot fall to LOW because the complete absence of species-specific data, and the uncharacterised state of the Indian Ocean food web pathway, mean we cannot confidently exclude meaningful impact. This is a lower research priority than thermal tolerance and oxygen dynamics, where the mechanisms are more direct and the oilfish depth range more clearly intersects documented change.

H4: Salinity

What Information IS Available:

Indian Ocean salinity dynamics — concentrated at the surface: The Indian Ocean's salinity field is shaped by large-scale precipitation-evaporation balances, freshwater inputs, and water mass circulation. The Arabian Sea maintains high surface salinity (35–37 psu) driven by intense evaporation and limited freshwater input. The Bay of Bengal sits at the opposite extreme (29–33 psu at the surface) due to massive freshwater discharge from the Ganges, Brahmaputra, and other rivers. The southern Indian Ocean, where SIOFA fishing operations concentrate, maintains stable oceanic salinity around 34–36 psu, characteristic of subtropical gyre water masses. Climate projections indicate that Indian Ocean surface salinity is changing in response to the intensifying global hydrological cycle — wet regions becoming wetter and dry regions becoming drier — with freshening in high-precipitation areas and increased salinity concentration in evaporation-dominated regions (IO Climate Summary). These changes are real and measurable.

For mesopelagic species the projected climate-driven changes — are concentrated in surface and near-surface waters. The 200–400 m depth range oilfish occupies is governed by the properties of intermediate water masses, not surface evaporation or precipitation. In the southern Indian Ocean, this depth range is occupied by Antarctic Intermediate Water (AAIW) and subtropical mode water, both of which are characterised by stable, well-

defined salinity signatures that change over decadal to centennial timescales, not interannually. The freshwater inputs that drive surface salinity variability in the Bay of Bengal, and the evaporative concentration in the Arabian Sea, do not propagate to 200–400 m depth in the SIOFA area.

The open-ocean, offshore character of oilfish distribution reinforces this insulation. The species occurs in oceanic waters over continental slopes and seamounts (Nakamura & Parin 1993; SIOFA 2025), remote from coastal freshwater inputs, river plumes, and estuarine salinity gradients. Coastal salinity stress — the mechanism by which climate-driven freshwater change could most rapidly affect near-shore species — is simply not a feature of oilfish habitat.

Marine teleosts are, in any case, competent osmoregulators across typical oceanic salinity ranges. Bony fish actively regulate ion and water balance against the external environment through gill transport, kidney function, and gut absorption. The salinity range encountered by oilfish across its global distribution (~34–36 psu in open-ocean habitats) is within the tolerance range of virtually all marine teleosts, and there is no theoretical basis for expecting osmoregulatory failure at projected salinity levels.

What Information IS NOT Available:

Oilfish salinity tolerance limits have not been measured. No osmoregulatory studies exist for *R. pretiosus* or close Gempylidae relatives. The precise salinity conditions in SIOFA fishing grounds at 200–400 m depth have not been reported specifically in relation to oilfish distribution. Projected salinity changes at mesopelagic depths in the south-central Indian Ocean under climate scenarios are not resolved at the spatial scales relevant to SIOFA seamount habitats.

These are genuine gaps, but their practical significance for this assessment is low. The argument for LOW applicability rests not on confirmed salinity tolerance data but on the physical oceanographic reality that oilfish habitat is structurally insulated from the salinity changes climate models project for surface waters.

Synthesis and Rating Justification:

Oilfish occupies open-ocean mesopelagic habitat at depths where salinity is determined by stable intermediate water mass properties, not by surface evaporation, precipitation, or freshwater input. The salinity changes projected under climate scenarios are concentrated in surface layers and coastal environments that are physically decoupled from oilfish habitat. The species' broad global distribution across oceanic water masses of similar salinity, combined with the general osmoregulatory competence of marine teleosts, further supports low vulnerability.

LOW is appropriate and represents a confident assessment rather than a data default — the physical oceanographic reasoning is robust. This is not a research priority; resources are better directed to hazards with genuine, direct exposure pathways. The salinity gap in

species-specific tolerance data is acknowledged but does not materially alter the assessment.

H5: Deoxygenation (OMZ Expansion)

What Information IS Available:

The Indian Ocean oxygen environment: The Indian Ocean contains more than 50% of the global oxygen minimum zone volume (IO Climate Summary). The Arabian Sea and Bay of Bengal host exceptionally intense OMZs, with mean oxygen concentrations around 10.45 µM and 14.51 µM respectively, and northern Arabian Sea values falling below 4 µM — essentially anoxic (IO Climate Summary; Dalpadado et al. 2023). These are not developing problems; they are established features of Indian Ocean biogeochemistry. The relevant question for climate vulnerability is whether they are changing — and the evidence is unambiguous that they are. Tropical Indian Ocean dissolved oxygen concentrations have decreased at 0.1–0.3 µmol kg^{-1} yr^{-1} over the past five decades, corresponding with sustained regional warming and intensified stratification that reduces the ventilation of intermediate waters (Dalpadado et al. 2023). CMIP6 model projections indicate subsurface O_2 concentrations at 100–600 m may decline by up to 30 µM under SSP5-8.5 by the end of the century (Dalpadado et al. 2023). The oilfish core depth range of 200–400 m sits squarely within this projected deoxygenation zone.

The mechanism of vulnerability — vertical habitat compression: Benthopelagic species like oilfish face a specific and well-described risk from OMZ expansion: vertical habitat compression. As OMZs expand upward and outward, species occupying mid-water depths face a narrowing band of physiologically tolerable habitat — warmer, less-dense water constraining downward movement from above, while expanding hypoxia constrains access to deeper water from below. Pörtner and Knust (2007) established the foundational framework: oxygen availability sets the effective thermal tolerance range, meaning that combined warming and deoxygenation generate synergistic stress that exceeds either stressor individually. For a species already living at 200–400 m and undertaking nightly vertical migrations to depth, OMZ expansion could compress both daytime habitat and the lower extent of the diel migration, reducing access to benthopelagic prey communities in deeper water.

The southern Indian Ocean — where the primary SIOFA oilfish fishery operates — is currently better oxygenated than the northern basin. Antarctic Intermediate Water ventilates southern Indian Ocean intermediate depths, maintaining oxygen levels substantially above Arabian Sea OMZ conditions. This provides a meaningful buffer: oilfish populations in Subareas 1 and 3b are not currently living on the edge of the OMZ. However, the directional trend toward deoxygenation is basin-wide, and the southern Indian Ocean is not immune to the long-term forcing that is reducing oxygen throughout the water column.

Interaction with warming: The deoxygenation hazard cannot be considered in isolation from H1 and H2. Warming reduces oxygen solubility directly — warmer water holds less dissolved oxygen at saturation — while simultaneously increasing fish metabolic rates,

raising oxygen demand at the same time supply is constrained. Stratification intensification, itself a product of surface warming, reduces the ventilation of intermediate waters by limiting exchange with well-oxygenated surface layers. These processes create a compounding dynamic: the same forcing (warming) simultaneously increases the metabolic oxygen demand of oilfish and reduces the oxygen available to meet that demand. This synergism means deoxygenation must be evaluated as part of a multi-hazard exposure, not as an independent stressor.

What Information IS NOT Available:

Oxygen tolerance thresholds have not been measured for *R. pretiosus* in any laboratory or field setting. Critical oxygen partial pressures — the levels at which performance begins to decline, at which avoidance behaviour is triggered, and at which survival is compromised — are entirely unknown. This is the fundamental gap preventing confident risk quantification: without knowing where the physiological boundary lies, it is impossible to assess whether projected oxygen declines will intersect that boundary.

Current dissolved oxygen concentrations in the SIOFA fishing grounds (Subareas 1 and 3b) at oilfish operating depths have not been reported in the SIOFA literature in relation to this species. Whether oilfish are currently distributed relative to oxygen gradients — avoiding low-oxygen areas, concentrating in better-oxygenated zones — is unknown. No comparative data exist from related Gempylidae species. Whether the diel vertical migration pattern is constrained at the lower depth range by oxygen (some mesopelagic species actively avoid low-oxygen water during nocturnal descent), or whether oilfish can tolerate OMZ-adjacent conditions, is unresolved.

The vertical extent and temporal trajectory of OMZ expansion specifically in the southern Indian Ocean seamount regions relevant to SIOFA is not resolved at the spatial and temporal resolution required for species-level assessment. Basin-scale projections confirm the directional trend; seamount-specific oxygen dynamics remain unquantified.

Synthesis and Rating Justification:

Deoxygenation in the Indian Ocean is among the best-documented and most physically grounded of the climate hazards reviewed here. The trends are robust, the mechanisms are understood, and the projected changes at depths directly corresponding to oilfish habitat are substantial. The hazard exposure is real. The vertical habitat compression mechanism — synergistic thermal and oxygen squeeze from above and below — is precisely the scenario of concern for a mesopelagic benthopelagic species operating at 200–400 m depth with nightly migrations to greater depths. MEDIUM–HIGH reflects this genuine concern.

The rating does not reach HIGH because the southern Indian Ocean retains better oxygenation than the northern basin, the absolute magnitude of projected decline at SIOFA depths remains uncertain, and — most importantly — oilfish oxygen tolerance thresholds are unknown, preventing confirmation that projected declines will intersect physiological limits. This is a HIGH-PRIORITY research gap: measuring oilfish oxygen tolerance

thresholds, and systematically monitoring dissolved oxygen at SIOFA fishing grounds in relation to catch distribution, are achievable steps that would substantially sharpen this assessment.

H6: Wind Stress

What Information IS Available:

Wind as the engine of Indian Ocean productivity: Wind stress is the primary driver of upwelling, mixed layer dynamics, and nutrient delivery to surface waters across the Indian Ocean. The southwest monsoon (June–September) generates intense coastal upwelling in the western Indian Ocean — the Somali Coast, Arabian Sea, and southwest Indian subcontinent — delivering cold, nutrient-rich water to the surface and supporting some of the most productive marine ecosystems in the tropics. The northeast monsoon drives a different but complementary circulation pattern. These wind-driven cycles determine the seasonal and interannual rhythm of primary productivity across much of the Indian Ocean, and are the upstream forcing on which the entire food web — ultimately including oilfish — depends.

The IO Climate Summary documents projected changes to monsoon intensity and timing under continued warming. Altered atmospheric temperature gradients modify the pressure systems that drive monsoon circulation, with potential effects on onset timing, duration, and intensity. Model projections show high inter-model variability in wind stress responses — some projections indicate intensified monsoon rainfall while others project weakening of specific wind-driven circulation features — making this one of the more uncertain elements of Indian Ocean climate projections. What is better established is that wind-driven upwelling strength in some regions has already changed, and that weakening upwelling in nutrient-delivery zones contributes to the declining productivity trends documented by the IO Climate Summary. Primary production is decreasing across large parts of the Indian Ocean, and altered wind-driven nutrient delivery is among the documented mechanisms.

The indirect pathway to oilfish: Oilfish at 200–400 m depth is physically insulated from direct wind effects. The species does not experience wind-driven surface mixing, wave action, or Langmuir circulation — the mechanisms by which wind directly affects epipelagic and near-surface species. The pathway from wind to oilfish is entirely indirect, operating through the vertical food web: wind drives upwelling → upwelling delivers nutrients → nutrients support phytoplankton → phytoplankton supports zooplankton → zooplankton supports mesopelagic fish and squid → these sustain oilfish. Each trophic step involves some efficiency loss and time lag, meaning that surface productivity changes do not translate immediately or proportionally to benthopelagic prey availability. However, the IO Climate Summary's projection of up to 40% zooplankton biomass decline by 2100 — driven partly by altered wind-productivity dynamics — indicates that the cumulative effect of food web cascades from surface forcing can reach the mesopelagic level with substantial magnitude.

The efficiency of this vertical pathway is influenced by the strength of biological carbon export — the flux of organic material from the productive surface layer to depth through sinking particles and diel migrating organisms. If wind-driven productivity declines reduce the density and diversity of diel migrating zooplankton and mesopelagic fish that connect surface and deep food webs, the supply of prey to benthopelagic predators like oilfish would decline even if other aspects of deep-sea ecology remain stable.

What Information IS NOT Available:

No studies have examined how wind-driven productivity changes cascade to benthopelagic prey availability at the depths and locations where oilfish occur in the SIOFA area. The translation of surface productivity signals to mesopelagic trophic dynamics is a major gap in Indian Ocean ecology generally, not just for this species. Seamount ecosystems may behave differently from open-ocean mesopelagic systems — topographic enhancement of local productivity through current-seamount interactions, Taylor column formation, and internal wave generation can partially offset regional productivity declines — but this has not been studied at SIOFA seamounts. Whether oilfish prey communities at 200–400 m in Subareas 1 and 3b are primarily supported by regional open-ocean productivity or by local seamount-scale enhancement is unknown.

Species-specific responses of oilfish to prey scarcity are uncharacterised. Whether the species can compensate for reduced prey availability through expanded foraging range, dietary switching (see S9), or deeper migration into richer benthopelagic zones is unknown. The interaction between wind-driven food web change and the other chronic stressors (warming, deoxygenation) — all of which also reduce prey availability through different mechanisms — would compound dietary stress in ways that cannot be assessed without baseline diet data.

Synthesis and Rating Justification:

Oilfish has no direct exposure to wind stress — depth insulates the species from the immediate physical effects of altered wind patterns. The hazard operates entirely through the indirect food web pathway, and the IO Climate Summary's documentation of declining primary productivity and projected zooplankton biomass collapse provides a credible basis for concern about the ultimate consequences for mesopelagic predators. AMBER reflects this balance: the mechanism is real and quantitatively supported at the food web level, but the multiple trophic steps between surface wind forcing and oilfish condition introduce substantial attenuation and uncertainty.

The rating does not reach MEDIUM–HIGH because oilfish's dietary generalism (S9: AMBER) provides meaningful buffering against taxon-specific prey shifts, and the indirect pathway means impacts are slower-acting and more compensable than direct thermal or oxygen stress. It does not fall to LOW because the projected scale of Indian Ocean zooplankton decline — 40% by 2100 — is large enough that dietary flexibility alone is unlikely to fully compensate if the mesopelagic prey base contracts broadly rather than simply shifting in composition.

H7: Current Change

What Information IS Available:

Indian Ocean circulation and its climate trajectory: The Indian Ocean's circulation is governed by monsoon-driven reversals in the north — the seasonally switching Somali Current, monsoon gyres, and countercurrents — alongside the more stable South Equatorial Current, subtropical gyres, and southern boundary currents including the Agulhas system. The IO Climate Summary documents that these systems are changing under continued warming, with projected slowdown of subtropical gyre circulation, alterations to the South Equatorial Current, and modifications to the cross-equatorial overturning circulation that ventilates intermediate waters. Changes to Indian Ocean Dipole and ENSO teleconnections further affect interannual circulation variability. These are not hypothetical future changes — some are already underway.

Larval dispersal as the primary exposure pathway: For a broadcast-spawning species producing pelagic eggs and larvae that drift passively with currents during their development, ocean circulation is not background scenery — it is the mechanism of population connectivity. Where larvae end up determines whether they recruit to suitable habitat or are lost to unsuitable environments. For oilfish, which concentrates on seamounts and continental slopes rather than occupying continuous habitat, this matters acutely: larvae must not merely survive the pelagic phase but must encounter suitable topographic features at settlement. Small shifts in current trajectories during the pelagic window can translate to large differences in where cohorts are delivered, and whether larvae find seamounts or are advected into open water where settlement is impossible. The oceanodromous classification (Nakamura & Parin 1993) and the hypothesised spawning migration (Vasilakopoulos et al. 2011) imply that adults move to specific locations to spawn — if those locations and the current pathways connecting them to recruitment habitat are altered, connectivity between spawning and nursery areas could be disrupted.

Adult movement: As an oceanodromous species capable of large-scale horizontal movement, adult oilfish also interacts with current systems as navigation infrastructure. Migratory species commonly use current systems as energetic highways or as orientation cues. Whether altered currents would benefit or hinder adult movements depends on the specific routes and cues used — neither of which is known for oilfish.

What Information IS NOT Available:

Oilfish larval ecology is entirely undescribed. Egg type is inferred from histological data (pelagic, oil-rich, buoyant; Vasilakopoulos et al. 2011) but larval duration has never been measured, larval vertical distribution is unknown, and the current systems that typically carry larvae from spawning areas to settlement habitat in the SIOFA region have not been characterised for this species. Without knowing how long larvae spend in the water column and how deep they reside during development, it is impossible to determine which current

layers are relevant to their dispersal or how altered circulation would affect their trajectories.

Adult horizontal migration routes, distances, and timing are undocumented. No tagging or tracking studies exist for oilfish in any ocean basin. Whether adults use specific current systems during spawning migrations, or whether movements are directed independently of currents, is unknown. Stock connectivity between SIOFA subareas — and between the Indian Ocean population and other basins — has not been assessed genetically, meaning the degree to which current-mediated connectivity currently maintains population structure is unresolved.

Synthesis and Rating Justification — LOW–MEDIUM

Ocean current changes represent a plausible but unquantifiable hazard for oilfish. The larval connectivity pathway is theoretically the most significant: a broadcast-spawning, seamount-associated species whose larvae must find discrete habitat features at settlement is inherently vulnerable to circulation changes that alter delivery trajectories. The adult movement pathway is secondary but not negligible for an oceanodromous species that migrates to spawn. Neither pathway can be assessed without baseline data on larval duration and dispersal, or adult movement routes. LOW–MEDIUM rather than MEDIUM reflects two partially offsetting considerations: the southern Indian Ocean circulation changes documented to date are less severe than northern basin changes, and oilfish's exceptionally broad global distribution implies that even if connectivity within one region is disrupted, the species is not at range-wide risk. It does not fall to LOW because the larval connectivity concern for a topography-dependent broadcast spawner is genuine and structurally important — not merely speculative. Larval ecology study, combined with genetic stock structure analysis, would be the most impactful research investment to resolve this indicator.

PART 2: Sensitivity and Adaptative Capacity Indicators

Part 2 evaluates the biological and behavioural characteristics that determine how oilfish would respond to the hazards identified in Part 1. Sensitivity indicators address the magnitude of likely response — how strongly a given hazard affects the species given its biology. Adaptive capacity indicators address the scope for adjustment — whether the species has the life history, mobility, flexibility, or ecological options to reduce adverse outcomes. Several indicators (thermal range, prey specificity, productivity, distributional range) are assessed in both parts because exposure and response capacity are related but distinct questions: knowing that a species occupies a thermally variable range tells you something about exposure; it tells you something different about whether the species can tolerate further change.

S1;A1: Thermal Range

What information IS available

Distribution as a thermal proxy: Oilfish occurs from 55°N to 43°S across the Atlantic, Pacific, and Indian Oceans (Nakamura & Parin 1993; FishBase 2025) — a latitudinal span encompassing substantial thermal variation. Tropical populations occupy surface waters reaching 28–30°C; temperate and higher-latitude populations encounter seasonal ranges of 8–20°C. At the core depth range of 200–400 m, temperatures are more thermally stable than at the surface, but still vary across the geographic distribution from approximately 10–22°C. The species' persistence across this gradient implies a minimum functional thermal envelope exceeding 10–15°C, which compares favourably with stenothermal deep-water specialists and suggests broad tolerance rather than narrow thermal niche.

The deep mesopelagic habitat provides meaningful buffering. The Azarian et al. (2023) documentation of marine heatwave penetration to 500 m depth in the southern Indian Ocean confirms that the 200–400 m zone is not thermally isolated from surface forcing, but temperature anomalies at depth are attenuated relative to surface extremes. A 3°C surface heatwave may manifest as less than 1°C at 300 m, depending on stratification.

Diel vertical migration complicates the thermal exposure picture. Portions of the oilfish population undertake nightly ascents from 200–400 m to near-surface depths (10–20 m) for feeding (Chinese Taipei SIOFA National Report 2020; Vasilakopoulos et al. 2011). During these migrations, individuals encounter the full range of surface thermal conditions, including marine heatwave anomalies and the full magnitude of the 1.2°C baseline warming documented in the Indian Ocean since 1950 (IO Climate Summary). This creates a dual thermal environment — moderately warmed benthopelagic daytime habitat and substantially warmed epipelagic nighttime feeding habitat — that non-migrating deep-water species do not experience.

What Information IS NOT Available:

No laboratory or experimental data exist on oilfish thermal physiology. Critical thermal maximum (CTmax), critical thermal minimum (CTmin), and thermal performance curves have not been measured for any population. Preferred temperature ranges are unknown. Acclimation capacity — the ability to shift physiological tolerance limits in response to sustained warming — has not been assessed. The relationship between the broad distributional thermal envelope and individual population thermal tolerance is unresolved: the species' wide range could reflect a single broadly tolerant lineage or multiple locally adapted populations with narrower individual tolerances, and these two scenarios carry very different implications for population-level vulnerability to warming.

Thermal requirements for early life stages are entirely undescribed. Dahlke et al. (2020), in a comprehensive analysis of 694 fish species, documented that eggs and larvae typically have thermal tolerance windows 2–3 times narrower than conspecific adults. If oilfish

follows this general pattern, reproductive success could be constrained at temperatures adults tolerate comfortably. Whether eggs developing in the surface layer (as expected from buoyant pelagic broadcast-spawned eggs) encounter warming beyond developmental tolerance is unknown.

Synthesis and Rating Justification — RED (inferred broad range)

The distributional evidence strongly suggests oilfish possesses a broad thermal range — the species occupies some of the warmest and coolest waters available within the subtropical ocean, and has done so across multiple ocean basins. This is genuine and informative. However, the RED rating reflects the complete absence of empirical thermal physiology data: CTmax, CTmin, thermal optima, and acclimation capacity are all unmeasured. We cannot determine whether Indian Ocean populations currently sit within optimal thermal conditions or near tolerance limits, whether the 1.2°C baseline warming has already imposed sublethal costs, or whether projected future warming will cross ecologically meaningful thresholds. The broad distribution provides a reasonable basis for inferring thermal generalism, but inference is not measurement. This is a HIGHEST PRIORITY gap for all temperature hazard assessments (H1, H2).

S2;A3: Mobility

What Information IS Available:

Oceanodromous classification: FishBase classifies oilfish as oceanodromous — undertaking migrations across oceanic regions (Nakamura & Parin 1993). This places it in the same behavioural category as many large pelagic fish that move at ocean-basin scales, distinct from demersal species that remain largely sedentary on a single seamount or shelf feature. The species' circumglobal distribution across three ocean basins, and its occurrence across widely separated seamounts and oceanic features within the SIOFA area, is consistent with substantial dispersal capacity over evolutionary timescales at minimum.

Demonstrated vertical mobility: The diel vertical migration behaviour documented across multiple sources demonstrates substantial short-term mobility — regular excursions of 200–800 m in the vertical dimension, nightly (Chinese Taipei SIOFA National Report 2020; Vasilakopoulos et al. 2011). This is energetically demanding behaviour, indicating that oilfish possess the physiological capacity and motivation to make large movements when circumstances require. The partial nature of the migration (not all individuals migrate on all nights; Vasilakopoulos et al. 2011) further suggests behavioural flexibility in movement decisions.

Gempylid morphology: Oilfish has the elongate, streamlined body form characteristic of the Gempylidae — a fast-swimming, active-pursuit predator family. The snake mackerel

body plan is associated with sustained swimming capacity rather than ambush or sedentary benthic strategies, supporting the inference of mobility.

Hypothesised spawning migration: Vasilakopoulos et al. (2011) hypothesised a spawning migration consistent with the oceanodromous classification. If confirmed, this would demonstrate directed horizontal movement over distances sufficient to aggregate at specific spawning sites — the kind of active habitat-seeking behaviour relevant to distributional shifts under climate change.

What Information IS NOT Available:

No tagging or acoustic tracking studies have been conducted on oilfish in any ocean basin. Horizontal movement rates, home ranges, and maximum migration distances are entirely unknown. Whether adults actively track favourable oceanographic conditions or habitat features, or move only for spawning, is unresolved. Stock connectivity between SIOFA Subareas 1 and 3b — where most catch is recorded — and other areas is unknown. Genetic stock structure analysis has not been conducted for oilfish. Whether the SIOFA population constitutes a single broadly connected stock or discrete subpopulations with limited exchange cannot be determined from available data.

The critical question for climate adaptation — can populations actively relocate in response to habitat degradation, and how quickly — remains completely unanswerable without tracking data. The species' demonstrated vertical mobility and oceanodromous classification suggest the capacity exists, but evidence for actual horizontal distributional shifts in response to environmental change is absent.

Synthesis and Rating Justification — AMBER

Convergent evidence — oceanodromous classification, circumglobal distribution, demonstrated large-scale vertical migration, and gempylid morphology — supports characterising oilfish as a highly mobile species. This is meaningful for climate vulnerability: high mobility reduces exposure by enabling distributional shifts in response to unfavourable conditions, and is one of the traits that contributes to the species' low FishBase vulnerability score (38/100) relative to the other SIOFA review species. AMBER rather than GREEN because horizontal movement capacity, migration distances, stock connectivity, and the population's actual ability to relocate at the pace of climate change are all unknown. Mobility is inferred from indirect indicators rather than measured.

S3;A2: Productivity

What Information IS Available:

Life history inference from body size and habitat: No quantitative productivity parameters — age at maturity, maximum age, von Bertalanffy growth parameters, natural mortality, fecundity — have been measured for oilfish in any population (see S8). What is

known is that oilfish is the largest species in the Gempylidae, reaching 2 m and 63.5 kg (Nakamura & Parin 1993), and occupies deep mesopelagic habitat. Across fish generally, large body size and deep benthopelagic lifestyle are associated with low productivity: slow growth, late maturity, low fecundity, and extended longevity. This is the life history syndrome of orange roughy, alfonsino, and other commercial deep-water species, all of which have proven highly vulnerable to fishing pressure precisely because their low productivity cannot sustain the removal rates that initially appear sustainable. The inference for oilfish — probable low productivity — is strong, but it remains inference.

SIOFA catch data and the observer database: The SIOFA Fisheries Overview (SC-10-14-Rev1, 2025) documents average annual catches of 13,530 tonnes over 2018–2022 — the highest of the three species in this review — almost entirely from the Chinese Taipei pelagic longline fleet. The observer database contains 21,192 weight measurements, 27,868 sex determinations, and 17 maturity assessments. These data represent a substantial, largely unanalysed resource. The 17 maturity assessments are insufficient for a maturity schedule, but they confirm that SIOFA observers have been collecting biological specimens — meaning future productivity estimates are achievable through targeted analysis of existing material combined with continued observer collection.

What Information IS NOT Available:

All quantitative productivity parameters are unknown. Age at maturity, maximum age, and growth rate (von Bertalanffy parameters) have never been published for *R. pretiosus*. Natural mortality cannot be estimated without these. Fecundity and spawning frequency are undescribed. Temperature effects on oilfish growth or reproduction have not been studied. Unlike alfonsino, where Pacific proxy data provide at least partial productivity estimates, no proxy species with published productivity data exist in close taxonomic proximity to oilfish within the Gempylidae.

The consequence is that population recovery time following perturbation cannot be estimated. If a climate-driven event or sustained overfishing reduces SIOFA oilfish abundance, we have no basis for predicting whether recovery would take 5 years or 50.

Synthesis and Rating Justification — RED (inferred LOW productivity)

The inference of low productivity from large body size, mesopelagic habit, and general deep-water fish life history patterns is well-supported by ecological principle. Low productivity substantially increases climate vulnerability: slower-recovering populations are less able to compensate for climate-driven mortality or reproductive failure, and longer generation times mean evolutionary adaptation lags far behind the pace of observed change. The RED rating reflects that while the productivity direction (low) can be inferred with reasonable confidence, every quantitative parameter required to characterise it precisely is absent. Otolith-based ageing of SIOFA observer samples, combined with analysis of the existing maturity and weight data, could substantially improve the evidence base without requiring new field programmes.

S4; A3: Distributional Range and Habitat Flexibility

One of the broadest distributions in deep-water fish: Oilfish occurs circumglobally from 55°N to 43°S across the Atlantic, Pacific, and Indian Oceans, including the Mediterranean (Nakamura & Parin 1993; FishBase 2025). This is an exceptionally wide distribution — comparable to the most broadly distributed pelagic tunas and swordfish — for a benthopelagic species primarily associated with mesopelagic depths. The distributional breadth implies tolerance of widely varying oceanographic conditions and demonstrates the species is not restricted to particular current systems, productivity regimes, or water mass characteristics.

Vertical habitat amplitude: Within this horizontal range, oilfish occupies 100–975 m depth (typically 200–400 m; Nakamura & Parin 1993). This substantial vertical range gives access to multiple ecological zones — epipelagic during nocturnal migrations, mesopelagic as primary habitat, and benthopelagic over continental slopes and seamounts. The ability to function across depth zones is not universal in deep-water fish; many species are constrained to narrower vertical bands. For oilfish, this vertical amplitude provides flexibility in responding to depth-specific habitat change.

Habitat associations: Within the available habitat, oilfish concentrates over continental slopes and seamounts (Australian Museum 2021; SIOFA 2025). In the SIOFA area specifically, catches are concentrated in the western region (Subareas 1 and 3b), though this likely reflects fishing effort distribution as much as genuine species absence elsewhere. The species is not restricted to the SIOFA area — it is a globally distributed ocean-basin species that is incidentally concentrated in SIOFA catch records by the distribution of fishing effort.

FishBase vulnerability score: The FishBase vulnerability score for oilfish is 38/100 — the lowest of the three species reviewed — with distributional breadth identified as a primary driver of this low score. This algorithmic assessment aligns with the biological reasoning: wide distribution provides spatial refugia, reduces the risk of range-wide climate impacts, and implies ecological flexibility.

What Information IS NOT Available:

Historical baseline distribution is uncharacterised — it is unknown whether the current SIOFA distribution pattern represents the species' natural range in that area or is an artefact of where fishing has occurred. Whether the concentration in Subareas 1 and 3b reflects genuine habitat preference, fishing effort, or both cannot currently be distinguished. Stock structure and connectivity across the SIOFA area and between the Indian Ocean and other basins are unknown. Whether the broad global distribution represents a single panmictic population or geographically isolated subpopulations with locally adapted ecologies has not been investigated genetically.

Synthesis and Rating Justification — GREEN

Oilfish possesses one of the broadest distributional ranges of any commercially significant deep-water species, with circumglobal distribution across three ocean basins and a substantial vertical depth range. This directly reduces climate vulnerability by providing spatial refugia — if conditions degrade in one part of the range, populations elsewhere are unaffected. The GREEN rating is warranted here: the distributional data are robust, well-documented in multiple authoritative sources, and directly informative about a genuine characteristic reducing vulnerability. This is the single strongest climate resilience factor for oilfish among all biological indicators reviewed, and explains why the species' aggregate vulnerability score is moderated relative to its data-poor life history parameters.

S5;A3: Environmental Cues Influencing Distribution

What Information IS Available:

Diel vertical migration as documented cue-driven behaviour: The partial diel vertical migration behaviour documented for oilfish — portions of the population ascending from 200–400 m to near-surface depths at night for feeding — is driven by environmental cues, most plausibly light intensity (Vasilakopoulos et al. 2011; Chinese Taipei SIOFA National Report 2020). This is the canonical trigger for vertical migration in mesopelagic species: light at depth decreases at dusk, reducing predation risk in shallower water and cueing ascent; light increases at dawn, cueing descent. The migration is not universal across individuals (Vasilakopoulos et al. 2011 found only some specimens captured at surface at night), suggesting the response is conditional rather than obligate — behavioural flexibility rather than rigid cue-dependence.

The conditionality is itself informative. Vasilakopoulos et al. (2011) proposed that migration behaviour is suppressed when benthopelagic prey is sufficiently available, with fish choosing the energetically cheaper foraging option. This means distribution is responsive to both light cues and prey availability, suggesting integration of multiple environmental signals rather than dependence on a single trigger.

Bathymetric preference: The species' consistent association with continental slopes and seamounts (Australian Museum 2021; Nakamura & Parin 1993) implies bathymetric habitat preferences that act as distributional cues. Whether this reflects active selection for topographic complexity, passive concentration by topography-enhanced prey aggregations, or some combination, the association is documented across multiple ocean basins and is therefore a robust distributional characteristic.

Oceanodromous behaviour and spawning migration: The oceanodromous classification and hypothesised spawning migration (Vasilakopoulos et al. 2011) imply responsiveness to seasonal environmental cues that trigger directed movement. The nature of these cues — temperature, photoperiod, endogenous rhythms, prey availability — is unknown, but the behaviour itself indicates environmental sensitivity rather than fixed, cue-independent movement.

What Information IS NOT Available:

The specific cue thresholds triggering or suppressing vertical migration are unknown. How climate-altered cues — reduced light penetration from phytoplankton blooms, shifting thermocline depth, altered prey distribution — would affect migration behaviour has not been studied. Seasonal distributional patterns are undocumented for any population: does distribution shift with season? Do adults aggregate at specific locations during the year? Spawning environmental triggers are completely unknown (see S7). Whether Indian Ocean populations are responsive to ENSO or IOD conditions that alter the physical environment is not established.

Synthesis and Rating Justification — AMBER

Oilfish shows documented responsiveness to environmental cues — diel light cycles, prey availability, and presumably seasonal triggers associated with the spawning migration — but none of the mechanisms have been characterised sufficiently to predict how behaviour would respond to climate-altered cue environments. The conditional rather than obligate nature of the vertical migration suggests flexibility that is a genuine resilience factor: a species that can modulate its behaviour based on environmental conditions is better equipped to respond adaptively to change than one locked into rigid behavioural programmes. AMBER reflects this partially positive picture: cue-responsiveness is documented and behavioural flexibility is evidenced, but the cue thresholds, seasonal patterns, and mechanisms remain unknown. For the spawning dimension specifically — where changed cue environments could have population-level reproductive consequences — the data gap is RED (see S7).

S6;A4: Reproductive Environmental Dependency and Spawning Strategy

What Information IS Available:

Spawning Strategy: Available evidence, though derived almost entirely from a single study in the eastern Mediterranean, is consistent with pelagic broadcast spawning. Vasilakopoulos et al. (2011) conducted the only published histological examination of *R. pretiosus* reproductive biology, documenting six oocyte developmental stages (perinucleolar through late vitellogenesis) and confirming that oilfish produce small, oil-rich, positively buoyant eggs released into the water column. Oocyte diameter at late vitellogenesis ranged from 224–366 µm. External fertilisation is implicit in this description — there is no evidence of nest-building, substrate attachment, or parental care in any studied population. Vasilakopoulos et al. (2011) hypothesised the occurrence of a spawning migration, consistent with the species' oceanodromous classification in FishBase (Nakamura & Parin 1993), which records offshore migrations as characteristic behaviour.

The observation of juvenile oilfish caught near the surface at night in Australian waters (Australian Museum, 2021) is consistent with a pelagic early life history following broadcast spawning — juveniles undergoing diel vertical migration from the mesopelagic

zone are precisely what one would expect from broadcast-spawned, oil-buoyed eggs that hatch into a surface-associated larval phase before recruiting to depth.

Spawning season: Mediterranean data place spawning in mid-to-late summer based on gonadal staging (Vasilakopoulos et al. 2011). No Indian Ocean or Southern Hemisphere spawning seasonality data exist. The species occupies a wide latitudinal range (55°N–43°S), and spawning phenology almost certainly varies between regions, as documented for other cosmopolitan mesopelagic species.

Egg characteristics and climate relevance: The oil-rich nature of the eggs is not incidental — the wax esters that make oilfish flesh notoriously indigestible to humans serve as a buoyancy mechanism throughout the animal's life cycle. Positively buoyant, lipid-laden eggs are a classic adaptation of broadcast-spawning mesopelagic predators, providing flotation and an energy reserve for the developing larva during extended pelagic drift. This reproductive strategy creates multiple environmental dependencies: fertilisation success depends on gamete encounter rates in open water; egg development and hatching are temperature-dependent; and larval survival requires encountering appropriate prey fields at the correct developmental stages, all without parental buffering.

Anomalous sex ratio: Vasilakopoulos et al. (2011) reported a strikingly skewed sex ratio of 1:8.4 in favour of females in the eastern Mediterranean longline catch. The cause is unresolved — it may reflect differential gear selectivity, sex-segregated habitat use, or genuine biological skew. The implication for reproduction is unclear but warrants documentation; if males occupy different depth strata or habitats, reproductive aggregation behaviour could be more complex than the available data suggest.

Broadcast spawning with oil-rich pelagic eggs creates substantial but poorly quantifiable environmental dependency. The Indian Ocean is warming at rates exceeding global averages (IO Climate Summary), with enhanced stratification and declining productivity documented across the basin. For a mesopelagic broadcast spawner, the principal climate risks include: disruption of prey availability during the pelagic larval phase through stratification-driven productivity declines; changes to current systems altering larval dispersal trajectories and connectivity between spawning and recruitment areas; and potential mismatch between thermally cued spawning timing and prey availability if warming shifts either phenology asymmetrically. The high lipid content of both adults and eggs may confer some resilience — wax esters provide an energy buffer during extended development — but this remains speculative. The lack of Indian Ocean spawning data makes it impossible to assess whether these hazards intersect with actual reproductive habitat.

What Information IS NOT Available:

Virtually all detail beyond the basic spawning strategy is absent. There are no published data on: spawning site characteristics (depth, temperature, habitat associations); whether adults aggregate to spawn or spawn in pairs consistent with their typically solitary or

paired adult behaviour; larval duration and dispersal pathways; environmental triggers for spawning (temperature thresholds, photoperiod, lunar cues); or age or size at first spawning. Critically, no reproductive data exist for Indian Ocean populations. Whether the Mediterranean spawning season translates to the SIOFA area is unknown. The hypothesised spawning migration (Vasilakopoulos et al. 2011) has not been confirmed, and its destination, trigger, and scale are entirely undescribed.

Synthesis and Rating Justification — AMBER

AMBER on the basis of Vasilakopoulos et al. (2011), which establishes the spawning strategy (pelagic broadcast spawning with oil-rich buoyant eggs), seasonal timing in one region (mid-to-late summer, Mediterranean), and evidence consistent with a spawning migration. This provides sufficient information to characterise the reproductive mode and its inherent environmental dependencies, supporting a partial vulnerability assessment.

Not GREEN because: spawning ecology data derive from a single study in one non-Indian Ocean location; Indian Ocean reproductive biology is entirely undescribed; environmental triggers, spawning site characteristics, larval duration, and migration details are unknown; and the anomalous sex ratio is unresolved.

S7: Spawning Cycle Sensitivity to Seasonal and Temperature Cues

What Information IS Available:

Seasonal Timing — A Single Data Point: The only published evidence bearing directly on spawning cycle comes from Vasilakopoulos et al. (2011), who staged gonads from eastern Mediterranean specimens and placed spawning in mid-to-late summer. This represents one region, one study, and a sample set that — by the authors' own acknowledgement — did not include individuals from the spawning period itself, limiting inference about cycle duration or intensity. Nonetheless, the finding of a clear seasonal signal is informative: oilfish are not spawning year-round in that region, and the mid-summer timing is consistent with temperature-dependent gonadal maturation following spring warming. Whether this timing is driven by temperature, photoperiod, endogenous rhythms, or some interaction of environmental cues is entirely unknown.

Inferred Seasonal Cueing from Latitudinal Biology: Oilfish occupy a wide latitudinal range (55°N–43°S), spanning a far broader thermal and photoperiodic gradient than the Mediterranean populations studied. In cosmopolitan mesopelagic species with comparable distributions, spawning timing typically varies latitudinally, with lower-latitude populations spawning earlier or over more extended periods than higher-latitude conspecifics. There is no empirical basis to apply this pattern to *R. pretiosus* directly, but it provides a reasonable prior expectation that spawning cycle timing is environmentally regulated rather than fixed. The species' oceanodromous classification (Nakamura & Parin 1993) and the hypothesised spawning migration (Vasilakopoulos et al. 2011) further imply that adults are responsive to seasonal environmental signals that trigger movement —

which would be inconsistent with an entirely endogenous, cue-independent reproductive cycle.

Depth Habitat and Cue Reception: A key complication for oilfish is that adults inhabit 200–1,000 m depth, with typical occupation at 200–400 m (FishBase; Nakamura & Parin 1993). At these depths, surface temperature signals are substantially attenuated and photoperiod is absent as a direct cue. If spawning timing is environmentally regulated, the relevant cues are likely to be: subsurface temperature changes propagating into the mesopelagic zone; changes in prey availability linked to seasonal production cycles; or internal endogenous rhythms entrained on longer timescales. None of these mechanisms have been investigated for oilfish. This is important for climate vulnerability assessment — if spawning is cued by subsurface thermal conditions rather than surface temperature, the Indian Ocean's documented warming penetration into the upper mesopelagic (Azarian et al. 2023, 100–500 m depth range) becomes directly relevant, but we cannot determine how.

What Information IS NOT Available:

The spawning cycle of *R. pretiosus* is almost entirely undescribed. Whether oilfish are serial spawners (releasing batches of eggs repeatedly across an extended season) or pulse spawners (concentrated single or few events) is unknown. Spawning duration is unknown. Whether spawning timing varies with latitude, temperature, or other environmental gradients across the species' range is unknown. No data exist from Indian Ocean populations. Whether the Mediterranean summer timing translates to the subtropical southern Indian Ocean, where the seasonal temperature cycle and productivity dynamics differ substantially, is entirely speculative. Temperature thresholds for spawning induction or cessation have never been measured. Phenological plasticity — the capacity to shift spawning timing in response to changing environmental conditions — has not been studied in any population.

The consequences of this data poverty for climate vulnerability assessment are significant. The Indian Ocean is warming at rates exceeding the global average (IO Climate Summary), with documented changes to stratification, productivity seasonality, and subsurface thermal structure. For a mesopelagic species whose spawning appears seasonally regulated, climate-driven alterations to the seasonal cue environment could shift spawning timing in ways that create mismatches between larval emergence and prey availability — the classic match-mismatch problem that has caused recruitment failures in other broadcast-spawning species experiencing phenological disruption. However, we cannot assess the magnitude or direction of this risk for oilfish without baseline data on what cues currently regulate the spawning cycle, what the spawning season actually is in the SIOFA area, and whether the population has the phenological flexibility to track shifting environmental conditions.

Synthesis and Rating Justification:

RED. The single seasonal observation from Vasilakopoulos et al. (2011) — mid-to-late summer spawning in the eastern Mediterranean — is insufficient to characterise spawning cycle sensitivity. It confirms seasonality but provides no information about: the cues that regulate it, the duration of the spawning period, serial versus pulse spawning strategy, latitudinal or regional variation, Indian Ocean timing, or temperature sensitivity.

Unlike S6, where sufficient information exists to characterise the spawning strategy and its inherent environmental dependencies, S7 requires knowledge of cycle regulation, duration, and sensitivity that is simply absent from the literature. The species' mesopelagic depth habitat adds an additional layer of complexity — the relationship between surface-level climate forcing and deep-water reproductive cueing is unknown and not straightforwardly inferred from shallower-water analogues.

If subsequent research or expert elicitation establishes that spawning timing in SIOFA waters is linked to a specific environmental window (e.g., post-austral summer thermocline development), this indicator could be revisited as AMBER.

S8: Age at Maturity

What Information IS Available:

Age and length at maturity — a global data gap: Neither age nor length at first maturity has been published for Ruvettus pretiosus in any ocean basin. FishBase, the primary global repository for fish life history parameters, records no maturity data for this species — the Lm field is explicitly marked as unknown. This is not a gap attributable to the limited duration of the SIOFA fishery or the absence of a stock assessment; the species has been taken as bycatch in tuna and swordfish longline fisheries worldwide for decades, yet no published study has documented age structure, growth parameters, or maturity schedules. The lack of otolith-based ageing studies in particular is striking given the species' wide commercial distribution.

What can be cautiously inferred comes from the species' life history context rather than direct measurement. Oilfish are large, mesopelagic, benthopelagic predators reaching 150 cm common length and maximum weights of 63.5 kg (Nakamura & Parin 1993). Across fish generally, large maximum size combined with deep mesopelagic habitat is strongly associated with late maturity, slow growth, and extended longevity — the K-selected life history strategy characteristic of species such as orange roughy, alfonsino, and other deep-water teleosts with which oilfish co-occurs in SIOFA waters. If oilfish follow this pattern, maturity may occur at several years of age and productivity would be low. However, this remains an inference from general life history theory rather than empirical evidence, and cannot substitute for measured data.

What Information IS NOT Available:

Age at first maturity, length at first maturity, growth, natural mortality, longevity, and fecundity are all undescribed in the published literature. No otolith collections or age validation studies have been conducted. Population abundance, biomass, and exploitation

rate are unknown. Whether Indian Ocean populations are structured as discrete stocks or constitute part of a broadly connected oceanic population is unresolved.

Synthesis and Rating Justification:

RED

Age at maturity has direct bearing on climate vulnerability: later-maturing species have longer generation times, slower population recovery rates, and extended windows of exposure before individuals contribute reproductively. The combination of probable late maturity, high sustained catch levels, and a warming, stratifying Indian Ocean with documented productivity declines (IO Climate Summary) creates a risk profile that cannot be quantified in the absence of basic demographic data. The absence of this information is itself a vulnerability — management cannot detect or respond to climate-driven productivity changes in a population whose baseline demographics are unknown.

No published age or length at maturity data exist for R. pretiosus in any population globally. FishBase records no maturity parameters. No otolith ageing studies have been conducted. Population health cannot be assessed without a stock assessment. The RED rating reflects a genuine global scientific gap in the published literature, not a deficiency specific to the SIOFA management context. Maturity parameters for this widely distributed and commercially significant bycatch species remain a conspicuous absence in the fisheries biology literature.

S9;A5: Prey Specificity and Dietary Flexibility

What Information IS Available:

Trophic position and feeding strategy: Oilfish occupy a high trophic level, estimated at 4.0–4.5, consistent with an apex mesopelagic predator feeding primarily on fish and cephalopods (FishBase 2025; Nakamura & Parin 1993). Global diet records from multiple ocean basins and fishing contexts consistently document a broad prey spectrum: teleost fish, cephalopods, and crustaceans are all reported (Nakamura & Parin 1993; FishBase 2025; Australian Museum 2021). Diet studies from the eastern Mediterranean (Vasilakopoulos et al. 2011) and the equatorial Atlantic around the St Peter and St Paul Archipelago (Viana et al. 2012) confirm benthopelagic fish as the numerically dominant prey, followed by cephalopods. Viana et al. (2012) identified 34 prey taxa in their sample — 16 fish species, 17 cephalopod species, and one crustacean — a taxonomic breadth that is characteristic of dietary generalism rather than specialist feeding.

The species' vertical migration behaviour reinforces this interpretation. Oilfish are typically solitary or paired near the bottom by day, migrating to shallower mesopelagic and epipelagic layers at night to feed (Nakamura & Parin 1993; Vasilakopoulos et al. 2011). This diel migration gives them access to a wide vertical range of prey communities — from demersal and benthopelagic fish near the bottom to epipelagic prey including, in one

documented case, flying fish (*Cheilopogon cyanopterus*) near the surface (Viana et al. 2012). Opportunistic exploitation of both vertical zones is precisely the behaviour expected of a generalist predator capable of switching prey in response to availability.

What Information IS NOT Available:

No stomach content analyses have been conducted on specimens from the southern Indian Ocean or the SIOFA area. The diet data that exist come from the Mediterranean and equatorial Atlantic — different oceanographic settings with different prey communities. Prey species identities, size selectivity, dietary composition by season, and ontogenetic diet shifts in Indian Ocean populations are all undescribed. Whether the generalist strategy inferred from Atlantic and Mediterranean populations applies equally to oilfish operating in the productive but rapidly changing southern Indian Ocean ecosystem cannot be confirmed without regional data.

Synthesis and Rating Justification

Amber. Sufficient global evidence supports classifying oilfish as a dietary generalist: broad prey taxonomic diversity, documented multi-taxa switching, and vertical migration accessing distinct prey communities across the water column all point to dietary flexibility. This inferred generalism reduces vulnerability to taxon-specific prey changes and justifies AMBER rather than RED. The rating does not reach GREEN because no Indian Ocean diet data exist — the generalist inference rests entirely on proxy populations in different oceanographic settings, and the projected magnitude of Indian Ocean prey community change under climate scenarios means this gap carries real management significance.

Generalised predators are typically buffered against prey-specific climate impacts — if one prey taxon declines, diet switching to alternative prey is possible. This is a meaningful resilience factor. However, the Indian Ocean Climate Summary projects up to a 40% decline in zooplankton biomass by 2100, driven by intensifying stratification and declining primary productivity. Zooplankton underpin the mesopelagic prey communities — small fish, squid, crustaceans — that form the base of the oilfish food web. A system-wide contraction in prey availability at this scale represents a different order of problem from taxon-specific prey decline; dietary flexibility is of limited value if the mesopelagic prey community contracts broadly rather than shifting in composition. The urgency of establishing baseline Indian Ocean diet data is amplified by this projection. Without knowing what oilfish actually eats in SIOFA waters, the pathway through which large-scale prey community change would affect condition, growth, and reproductive success cannot be assessed.

S10;A10: Competition for Habitat and Resources

What Information IS Available:

Intraspecific competition: The solitary or paired behaviour characteristic of oilfish (Nakamura & Parin 1993; FishBase 2025) suggests intraspecific competition for resources is low. Adults are not reported to form aggregations, schools, or feeding groups — behaviour that, in other species, generates density-dependent competition. If this social structure holds across the SIOFA population, crowding effects on feeding or habitat access are unlikely to be a significant factor under current conditions.

Escolar co-occurrence: The most obvious potential competitor is escolar (Lepidocybium flavobrunneum), a fellow gempylid that occupies overlapping mesopelagic depth ranges and shares a similar piscivore-cephalopod diet (Nakamura & Parin 1993). The two species are caught together in SIOFA longline operations and are aggregated in the same FAO catch category (SIOFA 2025, SC-10-14-Rev1), which itself reflects their ecological overlap. Whether this co-occurrence represents genuine competitive pressure, spatial partitioning, or simply shared habitat with negligible dietary interaction is unknown — no dietary overlap analysis has been conducted for either species in the Indian Ocean.

What Information IS NOT Available:

The benthopelagic community structure at 200–400 m in the SIOFA area is poorly characterised. The identity, abundance, and trophic roles of other potential competitors — grenadiers, oreosomatids, and other mesopelagic predators present at comparable depths — have not been systematically documented. Without Indian Ocean diet data for oilfish (see S9), dietary overlap with co-occurring species cannot be quantified. Competitive dominance hierarchies, resource partitioning mechanisms, and the degree to which oilfish and escolar functionally separate their ecological niches despite habitat overlap are all unknown. Should the Indian Ocean's projected warming and productivity declines drive habitat compression — forcing species currently distributed across a broad depth range into a narrower thermal window — competition between co-occurring mesopelagic predators could intensify. Whether oilfish would be advantaged or disadvantaged relative to escolar and other competitors under such conditions cannot be assessed from the available literature.

Synthesis and Rating Justification — RED

Competition dynamics for R. *pretiosus* in the southern Indian Ocean are essentially unknown. The solitary social structure provides weak evidence that intraspecific competition is low, and the well-documented co-occurrence with escolar identifies the most plausible interspecific competitor, but neither dietary overlap nor ecological partitioning has been studied. RED reflects the complete absence of community ecology data from the SIOFA area. This is a lower priority gap than thermal tolerance, reproductive biology, and productivity (S1, S6–S8), where data deficiencies more directly constrain vulnerability assessment. It is unlikely to be resolved without targeted community trawl surveys or baited camera deployments at representative SIOFA fishing depths — studies that are not currently planned.

References

A

Animalia.bio (n.d.) *Ruvettus pretiosus* https://bie.ala.org.au/species/https://biodiversity.org.au/afd/taxa/bafc5a30-0f60-4dc7-aa18-ed0189fc12c9

Australian Museum (2021) Oilfish, *Ruvettus pretiosus* Cocco, 1833. Australian Museum, Sydney. https://australian.museum/learn/animals/fishes/oilfish-ruvettus-pretiosus/

Azarian, C., Bopp, L., Sallée, J.-B., Swart, S., Guinet, C. and d'Ovidio, F. (2024) Marine heatwaves and global warming impacts on winter waters in the Southern Indian Ocean. *Journal of Marine Systems*, 243, p.103962. https://doi.org/10.1016/j.jmarsys.2023.103962

Note: Published online 2023, in print 2024. Cited in this review as Azarian et al. (2023).

C

Chakraborty, K., Joshi, A. P., Ghoshal, P. K., Baduru, B., Valsala, V., Sarma, V. V. S. S., et al. (2024). Indian Ocean acidification and its driving mechanisms over the last four decades (1980–2019). Global Biogeochemical Cycles, 38, e2024GB008139. **https://doi.org/10.1029/2024GB008139**

Chinese Taipei (2020) National Report to the SIOFA Scientific Committee. 30 March – 3 April 2020, Saint Gilles, Reunion

Cox, H.E. and Reid, E.H. (1932) The chemical composition of oil of Ruvettus pretiosus, the castor oilfish. *J Am Chem Soc* 54(1)

D

Dahlke, F.T., Wohlrab, S., Butzin, M. and Pörtner, H.-O. (2020) Thermal bottlenecks in the life cycle define climate vulnerability of fish. *Science*, 369(6499 https://doi.org/10.1126/science.aaz3658

Dalpadado, P., Roxy, M.K., Arrigo, K.R., van Dijken, G.L., Chierici, M., Ostrowski, M., Skern-Mauritzen, R., Bakke, G., Richardson, A.J. and Sperfeld, E. (2024) Rapid climate change alters the environment and biological production of the Indian Ocean. *Science of the Total Environment*, 906.

Note: Published online 2023, in print 2024. Cited in this review as Dalpadado et al. (2023).

F

FishBase (2025) *Ruvettus pretiosus* Cocco, 1833 [online]. FishBase. Available at: https://www.fishbase.org [Accessed 2025].

I

IUCN (2012) *Ruvettus pretiosus*. The IUCN Red List of Threatened Species. Least Concern. Available at: https://www.iucnredlist.org/species/190432/16644022 [Accessed 2025].

K

Kryc, K. (2026) Summary Document: Climate Change Impacts on the Indian Ocean. Prepared for the 11th Annual Meeting of the Southern Indian Ocean Fisheries Agreement (SIOFA) Scientific Committee. [Attachment F]

Note: Cited throughout this review as 'IO Climate Summary' or 'IO Climate Summary (2026)'.

N

Nakamura, I. and Parin, N.V. (1993) FAO Species Catalogue Vol. 15: Snake mackerels and cutlassfishes of the world (families Gempylidae and Trichiuridae). *FAO Fisheries Synopsis*, No. 125, Vol. 15. Rome: FAO

P

Pörtner, H.O. and Knust, R. (2007) Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science*, 315(5808). https://doi.org/10.1126/science.1135471

S

SIOFA (2025) Overview of SIOFA Fisheries 2025. SC-10-14-Rev1. 10th Meeting of the Scientific Committee. Southern Indian Ocean Fisheries Agreement.

T

Te Papa Museum (2023) https://blog.tepapa.govt.nz/2023/05/08/the-good-oil-fish-findings-on-the-sea-floor/

V

Vasilakopoulos, P., Pavlidis, M. and Tserpes, G. (2011) On the diet and reproduction of the oilfish *Ruvettus pretiosus* (Perciformes: Gempylidae) in the eastern Mediterranean. *Journal of*

the Marine Biological Association of the United Kingdom, 91(4), pp.873–881. https://doi.org/10.1017/S0025315410001785

Note: Published online 2010, in print 2011.

Viana, Danielle & Travassos Tolotti, Mariana & Porto, Mariana & Araújo, Rodolfo & Vaske Júnior, Teodoro & Hazin, Fábio. (2012). Diet of the oilfish Ruvettus pretiosus (Perciformes: Gempylidae) in the Saint Peter and Saint Paul archipelago, Brazil. *Brazilian Journal of Oceanography*. 60. 10.1590/S1679-87592012000200008.