SOUTHERN INDIAN OCEAN FISHERIES AGREEMENT

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

Contract CLI-2025-01

ANNEX 2

Literature Review

Alfonsino/Beryx Splendens

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 alfonsino (*Beryx splendens*) in the SIOFA Area.

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: alfonsino as a species (direct physiological and behavioural impacts); seamount habitat characteristics (physical and structural changes to the environment the species occupies); and food web and prey availability (indirect effects operating through the trophic pathways that sustain alfonsino). 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 alfonsino 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: Alfonsino Biology, Habitat, and Food Web

Alfonsino as a Species: Biological Characteristics

Beryx splendens (alfonsino) is a benthopelagic fish in the family Berycidae with circumglobal subtropical distribution from 45°N to 43°S across Atlantic, Pacific, and Indian Oceans. In SIOFA, populations occur across Subareas 2-4 with reported catches averaging 3,698 tonnes annually (SIOFA 2025, SC-10-14-Rev1). Middleton et al. (2023) initiated genetic stock structure analysis across SIOFA seamounts, though comprehensive assessment remains incomplete.

Depth distribution: Alfonsino inhabit 25–1,300m depths, with concentrations at 400–600m on seamounts (SIOFA 2025). This mesopelagic depth range positions them below the surface mixed layer but within depths affected by subsurface warming. The IO Climate Summary documents that warming-driven stratification is driving thermal anomalies into the upper mesopelagic zone, making this depth range less insulated from surface forcing than previously assumed. The species shows strong seamount association (Lehodey et al. 1994), aggregating over topographic features rather than dispersing across open ocean habitat.

Life History Strategy: Alfonsino exhibit K-selected traits indicating low productivity and slow recovery. Lehodey et al. (1997) documented sexual maturity at 6-8 years in New Caledonian populations. Critically, the SIOFA Age Validation Study (2023) for the congener B. decadactylus revealed longevity of 50-70 years using radiocarbon dating—3-5 times higher than previous estimates from whole otolith counts (10-25 years). If B. splendens shares similar longevity, this fundamentally alters productivity assessments. Late maturity combined with potentially extended longevity creates high vulnerability to overfishing and environmental perturbations due to slow recovery rates.

Physiological Characteristics: Lehodey & Grandperrin (1996) established that alfonsino growth rates respond to temperature variability with a 7.5-month lag to ENSO cycles in Pacific populations (23-25°S). Otolith annuli measurements showed El Niño events (warmer temperatures) increased growth rates while La Niña events (cooler) reduced them, demonstrating clear temperature-growth linkages mediated through oceanographic variability.

et al. (2015) documented metabolic enzyme activity, measuring lactate dehydrogenase (LDH) at 190.2 µmol/g tissue, suggesting metabolic flexibility that might indicate capacity to function under low oxygen through anaerobic metabolism. However, specific thermal tolerance limits (CTmax/CTmin), oxygen requirements, and acidification sensitivity remain completely unstudied for Indian Ocean populations.

Reproductive Biology: Lehodey et al. (1997) documented spawning aggregations on specific seamounts in New Caledonian waters, indicating site fidelity and environmental

dependency for reproduction. Spawning seasonality and environmental triggers (temperature, lunar cycles, current patterns) are not characterised for Indian Ocean populations. Mundy (1990) noted an extended larval period, creating a vulnerability window where early life stages may be exposed to unsuitable environmental conditions. Fecundity data are absent for Indian Ocean alfonsino.

Seamount Habitat Characteristics

Alfonsino are strongly associated with seamount habitats across their global range. Lehodey et al. (1994) documented this association in Pacific waters, with commercial catches concentrated over seamount topography. In SIOFA waters, catches occur primarily across seamount features in Subareas 2, 3a, 3b, and 4 — predominantly the western SIOFA Area (SIOFA 2025). Fleet composition includes Australia, Cook Islands, Japan, and Korea, using midwater trawl. Stock structure is divided into West and East management units (Brandão et al. 2021). Seamounts create distinct oceanographic features through current-topography interactions that enhance local productivity, attract prey aggregations, and provide structured habitat for demersal species.

The typical depth range of 400–600m positions alfonsino in the mesopelagic zone, characterised by: (1) reduced light penetration limiting primary production; (2) temperature stability compared to surface waters, but not immunity to subsurface warming — the IO Climate Summary documents that marine heatwaves penetrate to mesopelagic depths, directly overlapping alfonsino's primary depth range; (3) intermediate oxygen concentrations between well-oxygenated surface and deep waters; and (4) dependence on vertical flux of organic matter from surface productivity.

Seamounts interact with ambient currents to generate localised oceanographic features including: (1) Taylor columns (trapped rotating water masses over seamount summits), (2) current acceleration around seamount flanks, (3) lee retention zones where particles and organisms accumulate, and (4) enhanced vertical mixing delivering nutrients to the photic zone. These processes depend on current speed, direction, and stability. Wind-driven and thermohaline circulation changes under climate scenarios could alter current patterns, potentially affecting seamount productivity mechanisms.

Habitat Constraint and Climate Vulnerability: Unlike mobile pelagic species that can track optimal conditions by shifting distribution, alfonsino's seamount association constrains habitat flexibility. If environmental conditions at a seamount deteriorate (warming, deoxygenation, acidification, reduced productivity), alfonsino face three options: (1) tolerate degraded conditions (depends on physiological tolerance limits — unknown), (2) shift to deeper depths on the same seamount (if suitable habitat exists and physiological limits permit), or (3) relocate to different seamounts (depends on adult mobility and whether alternate sites exist within dispersal range). This habitat constraint increases vulnerability compared to species with continuous habitat across depth and latitude gradients.

Seamount productivity depends critically on current patterns. Changes to current strength, direction, and seasonal structure driven by climate change — particularly the documented 11–23% weakening of the Agulhas Current and associated South Indian Ocean circulation slowdown noted in the IO Climate Summary — could alter or eliminate the productive upwelling dynamics that make seamounts valuable habitat. This is explored in detail under H7.

Food Web and Trophic Ecology

Kodama et al. (2025) provided the most comprehensive alfonsino dietary analysis to date, examining 708 stomachs from Pacific populations. Diet composition comprised: micronektonic fish (48.6%), shrimp/decapod crustaceans (24.3%), and squid/cephalopods (15.7%). Horn et al. (2010) similarly documented consumption of midwater prey including myctophids (lanternfish) and other mesopelagic species. This dietary breadth indicates a generalist predatory strategy, feeding opportunistically on available mesopelagic prey rather than specialising on specific species. Alfonsino are secondary/tertiary consumers in seamount food webs.

Mesopelagic prey populations ultimately depend on surface primary productivity through vertical carbon flux pathways. The IO Climate Summary documents declining net primary production trends across Indian Ocean regions, driven by warming-induced stratification and weakened upwelling. These surface changes affect mesopelagic food webs through: (1) reduced particulate organic matter flux to depth, (2) altered zooplankton community composition and abundance, (3) changes to diel vertical migration patterns, and (4) potential shifts in micronekton distributions.

The connection between surface productivity and mesopelagic prey involves multiple trophic steps: surface phytoplankton → zooplankton → micronekton (small fish, shrimp, squid) → alfonsino. Each transfer involves energy loss (typically ~10% efficiency), meaning changes in primary productivity have amplified effects at higher trophic levels. Seamount systems may have enhanced productivity compared to open ocean due to current-driven upwelling and nutrient injection, potentially buffering against basin-scale productivity declines.

The generalist diet documented by Kodama et al. (2025) suggests alfonsino may have some capacity to shift prey selection if specific prey types decline. The approximately equal contributions of fish (48.6%), shrimp (24.3%), and squid (15.7%) indicate no single prey type dominates. This dietary breadth could provide resilience if climate impacts affect prey groups differentially. However, no Indian Ocean dietary data exist — we assume Pacific patterns represent SIOFA populations, but regional differences in prey availability could result in different prey selection.

The IO Climate Summary documents a 300% increase in compound MHW and low-chlorophyll events across specific Indian Ocean provinces — quantifying this food-web disruption pathway as a concrete, documented consequence of thermal forcing rather than a theoretical concern.

This baseline characterisation establishes the biological context, habitat characteristics, and food web structure essential for evaluating how climate hazards affect alfonsino populations. Each hazard assessment (H1–H7) that follows examines impacts across these three dimensions: species biology, seamount habitat, and trophic ecology.

Part 1: Hazard Indicators (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: alfonsino as a species, the seamount habitats it occupies, and the food web that sustains it. The purpose is to identify which hazards are materially relevant to alfonsino and through what pathways — the foundation on which the sensitivity assessment in Part 2 is built.

H1: Marine Heatwaves

What Information IS Available:

Indian Ocean Regional Trends: The IO Climate Summary documents that the Indian Ocean is warming faster than any ocean except the Arctic, with SST projections of +1.7 to +3.8°C per century depending on emission scenarios. The Indian Ocean Warm Pool (IOWP), defined as waters >28°C, has expanded significantly from 1982-2021, particularly into northern-central basins. The IO Climate Summary confirms the Indian Ocean holds the key strategic position as the fastest-warming ocean basin globally.

Marine heatwave frequency and intensity are increasing across the Indian Ocean. The IO Climate Summary reports that the tropical Indian Ocean is approaching a near-perpetual marine heatwave conditions by end of century, representing a restructured baseline rather than episodic extreme events.

Subsurface warming: The IO Climate Summary specifically documents marine heatwaves and their impacts on Southern Indian Ocean winter waters at 100-500m depths. This study demonstrated that MHWs are not purely surface phenomena - they penetrate below the mixed layer into the upper mesopelagic zone. Winter water masses (the remnant of the previous winter's mixed layer) showed warming trends, indicating sustained thermal impacts at depth.

Temperature variability trends: The IO Climate Summary documents that years of the first decade (1998-2008) showed more often cooler temperatures and higher productivity, whereas years of the last decade (2009-2019) showed more often warmer temperatures and lower productivity, with some recovery in very recent years (2017-2019). The study covered an area of ~38 million km² including the south-central Indian Ocean basin relevant to alfonsino habitat.

Species-specific temperature sensitivity: Lehodey & Grandperrin (1996) established in New Caledonian waters (Pacific Ocean, 500-900m depth on seamounts) that alfonsino growth rates are strongly correlated with temperature fluctuations in the 0-500m water

layer. Growth rate variations, measured through otolith annuli width, responded to ENSO-driven temperature changes with a 7.5-month time lag at 23-25°S latitude. El Niño events (warmer temperatures) increased growth rates, while La Niña events (cooler temperatures) reduced growth rates. This demonstrates clear temperature-growth linkages mediated through oceanographic variability.

What Information IS NOT Available:

No Indian Ocean-specific data exist on alfonsino thermal tolerance limits or optimal temperature ranges at their typical depth range (300-1200m). The Pacific study by Lehodey & Grandperrin (1996) establishes temperature-growth relationships but does not define upper or lower thermal tolerance thresholds that would cause mortality or reproductive failure.

The rate and magnitude of subsurface warming specifically at 300-1200m depths in the SIOFA Area is not well characterised. While Azarian et al. (2023) examined 100-500m depths, the deeper demersal zone (600-1200m) where alfonsino also occur lacks equivalent MHW propagation studies.

Seamount thermal dynamics and how MHWs affect seamount-associated species are poorly understood. Seamounts may create localised thermal refugia or may experience intensified thermal stress depending on current patterns and upwelling dynamics, but no studies address this for Indian Ocean seamounts relevant to alfonsino.

No empirical studies examine alfonsino physiological responses to sustained thermal stress or define temperature thresholds for growth impairment, reproductive failure, or mortality. The Lehodey & Grandperrin (1996) study shows correlation between temperature and growth but does not establish causative mechanisms or stress thresholds.

Synthesis and Rating Justification:

An AMBER rating reflects moderate applicability of temperature extreme hazards to alfonsino. On one hand, we have strong regional evidence that the Indian Ocean is experiencing unprecedented warming and increasing MHW frequency (IO Climate Summary), with warming penetrating to mesopelagic depths (IO Climate Summary). We also have species-specific evidence from Pacific populations that alfonsino growth responds to temperature variability (Lehodey & Grandperrin 1996).

However, alfonsino's depth distribution (300-1200m) provides substantial buffering from extreme surface temperature events. The primary concern is not acute thermal stress during MHWs, but rather cumulative effects of sustained warming on metabolism, growth rates, prey availability, and potential habitat displacement. The deeper demersal zone appears to experience more stable temperatures than surface waters, moderating direct exposure to temperature extremes.

Critical uncertainty remains around thermal tolerance limits and stress thresholds. Without knowing at what temperature alfonsino experience reduced fitness, reproductive failure, or mortality, we cannot definitively assess whether projected warming scenarios will cause direct thermal impacts or whether effects will be primarily mediated through ecosystem changes (prey availability, competition, habitat quality).

The rating is not GREEN because we lack Indian Ocean-specific physiological data and cannot quantify exposure at relevant depths. The rating is not RED because we do have regional warming documentation and proxy evidence of temperature sensitivity. AMBER appropriately reflects moderate concern based on available evidence while acknowledging significant knowledge gaps.

H2: Increased Sea Surface Temperature

What Information IS Available:

Magnitude of SST increase: The IO Climate Summary quantifies SST increases across 11 Indian Ocean regions over 22 years (1998-2019) using satellite data. The south-central Indian Ocean basin, which encompasses key alfonsino seamount habitat, showed the highest regional SST increase of ~0.9°C over this period (1982–2021) — the basin-wide average was ~0.7°C.

IOWP expansion: The Indian Ocean Warm Pool (>28°C) has expanded dramatically in recent decades — the IO Climate Summary documents coverage approaching 100% of the northeast and central Indian Ocean. This represents a fundamental shift in the thermal structure of the region, with implications for stratification, mixed layer depth, and vertical nutrient fluxes.

Primary productivity impacts: The IO Climate Summary documents declining net primary production (NPP) trends in several northern Indian Ocean regions. The decline is attributed to increased stratification and nutrient depletion in surface waters as warming intensifies. Years of the last decade (2009-2019) showed more often warmer temperatures and lower productivity except in very recent years (2017-2019) when productivity was high. The southwest monsoon was confirmed as a key driver of seasonal chlorophyll-a patterns in major upwelling areas.

The IO Climate Summary provides complementary evidence of declining Indian Ocean primary productivity, identifying key drivers including warming-induced stratification. This food web foundation impact has cascading implications for mesopelagic consumers like alfonsino that depend on vertical flux of organic matter and prey populations.

Temperature-growth relationship: Lehodey & Grandperrin (1996) established that alfonsino growth rates respond to temperature variability in Pacific populations, with

demonstrated linkages to ENSO cycles. Specifically, otolith annuli measurements showed width variations correlating with temperature in the 0-500m layer with a 7.5-month lag. This provides proxy evidence that sustained SST increases could affect alfonsino productivity through direct metabolic effects.

What Information IS NOT Available:

No empirical data document Indian Ocean alfonsino distribution shifts in response to warming trends. While other fish species have shown poleward range shifts with warming, alfonsino's seamount association constrains their distribution flexibility compared to fully pelagic species. Whether populations can track suitable thermal envelopes by moving deeper or to higher latitudes is unknown.

Temperature thresholds for productivity or mortality impacts at mesopelagic depths are not established. The Lehodey & Grandperrin (1996) study shows growth responses to temperature variability but does not define optimal temperature ranges or stress thresholds. We cannot predict at what temperature increases growth rates plateau or decline.

Prey field responses to warming in south-central Indian Ocean seamount ecosystems are poorly documented. While IO Climate Summary shows regional NPP trends, the translation of surface productivity changes to mesopelagic prey availability for alfonsino is not quantified. Seamount food webs may differ from open ocean systems due to enhanced local productivity from current interactions.

Interactive effects between SST increase and other stressors (deoxygenation, acidification) are not studied for alfonsino. Warming may compress suitable habitat if coupled with oxygen minimum zone expansion or acidification of deeper waters.

Synthesis and Rating Justification:

The AMBER rating reflects moderate-high applicability with moderate confidence. The substantial body of evidence on Indian Ocean SST increases (IO Climate Summary) combined with species-specific temperature sensitivity data (Lehodey & Grandperrin 1996) supports moderate concern. The south-central Indian Ocean basin where alfonsino occur has experienced the highest regional warming (+0.7°C), and this warming has ecosystem-level consequences through NPP declines (IO Climate Summary).

However, alfonsino’s deeper distribution (300-1200m) provides buffering from direct SST exposure. The primary pathways of impact are likely indirect through food web disruption rather than direct thermal stress. The established temperature-growth relationship from Pacific populations suggests productivity could decline if thermal conditions exceed optimal ranges or if prey availability decreases due to food web disruption.

Stock displacement is plausible but unquantified. Seamount-associated species may shift to higher latitudes or deeper depths if their preferred thermal envelope migrates, but their association with specific geomorphic features constrains distributional flexibility compared to pelagic species. No empirical evidence documents such shifts in Indian Ocean alfonsino populations.

The rating acknowledges substantial regional warming combined with demonstrated species sensitivity, balanced against uncertainty about thermal tolerance limits, depth-buffering effects, and actual responses of Indian Ocean populations. More confident assessment requires: (1) Indian Ocean-specific thermal tolerance data, (2) time series of distribution/abundance relative to environmental covariates, and (3) prey field monitoring at seamount sites.

H3: Ocean Acidification

What Information IS Available:

Indian Ocean acidification trends: The IO Climate Summary provides comprehensive documentation of Indian Ocean acidification over the last two decades. The study examined surface and subsurface pH changes, identifying driving mechanisms including anthropogenic CO_2 uptake, warming-induced CO_2 solubility changes, and alterations to the carbonate system. The Indian Ocean is experiencing measurable pH declines consistent with global acidification trends.

Spatial patterns: The IO Climate Summary shows that acidification is not uniform across the Indian Ocean. The Arabian Sea and Bay of Bengal exhibit distinct pH dynamics driven by regional processes (upwelling, freshwater input, biological productivity). The southeastern Indian Ocean, where alfonsino seamount habitat is concentrated, is identified by the IO Climate Summary as an acidification hotspot — driven by a combination of anthropogenic CO_2 uptake and warming-reduced gas solubility. This represents a materially different characterisation from sources that suggested the southern IO was lower-concern relative to northern regions.

Depth-specific changes: The study documented that acidification affects not only surface waters but propagates into the thermocline and intermediate depths through water mass formation and circulation. Mesopelagic waters (200-1000m) where alfonsino occur are subject to acidification, though the magnitude and rate of change at 300-1200m depths specific to SIOFA seamount areas is not well resolved.

What Information IS NOT Available:

No studies examine alfonsino sensitivity to ocean acidification whatsoever. There are zero published data on physiological responses, calcification impacts, behavioural

changes, or fitness consequences of reduced pH for any Beryx species from any ocean. This represents a complete knowledge gap.

Alfonsino possess otoliths (ear stones made of calcium carbonate) and scales with calcified elements, but whether acidification affects otolith formation, scale integrity, or skeletal development is entirely unknown. Other fish species show varied responses to acidification, but without empirical data for alfonsino we cannot assume sensitivity or tolerance.

Prey field impacts of acidification in mesopelagic seamount ecosystems are poorly characterised. Acidification may affect alfonsino indirectly through impacts on prey species (zooplankton, small fish, crustaceans), but the cascading effects through seamount food webs remain speculative.

The interaction between acidification and other stressors (warming, deoxygenation) at mesopelagic depths relevant to alfonsino is not studied. Multiple stressors may have synergistic effects that exceed impacts of single stressors, but this cannot be evaluated without baseline physiological data.

Spatial resolution of acidification projections at seamount scales is insufficient. Seamounts may experience enhanced or reduced acidification impacts depending on local current patterns, upwelling dynamics, and biological activity, but fine-scale modelling does not exist for SIOFA seamount features.

Synthesis and Rating Justification:

The RED rating reflects a critical knowledge gap where we cannot assess hazard applicability due to complete absence of species-specific information. While IO Climate Summary provides excellent documentation of Indian Ocean acidification trends, we have zero data on whether alfonsino are sensitive to these changes.

Acidification is occurring in the Indian Ocean, including at mesopelagic depths, so exposure is documented. However, exposure without sensitivity data cannot determine vulnerability. Other deep-sea fish species show varied responses to acidification - some are tolerant while others exhibit physiological stress, behavioural impairment, or reproductive failure.

Without empirical studies, we cannot determine if: (1) alfonsino physiology is directly affected by pH changes, (2) calcified structures (otoliths, scales) are impaired, (3) sensory systems are disrupted affecting feeding or predator avoidance, (4) reproductive processes are compromised, or (5) prey populations shift affecting food availability.

The RED rating indicates this is a high-priority research gap requiring experimental studies to establish baseline sensitivity. Cannot be addressed through expert elicitation alone - requires laboratory or field experiments examining alfonsino physiological

responses across projected pH scenarios. The rating could shift to AMBER or GREEN with sensitivity data, or remain RED if species proves highly sensitive but management options are limited.

H4: Salinity Changes

What Information IS Available:

Salinity at mesopelagic depths (300-1200m) in the southern Indian Ocean is relatively stable compared to surface waters. IO Climate Summary noted that salinity changes in the Indian Ocean are primarily concentrated in surface layers and coastal regions influenced by precipitation patterns, river runoff, and evaporation. The south-central Indian Ocean basin where alfonsino occur experiences minimal salinity variability due to distance from major freshwater inputs and below the influence of surface precipitation/evaporation cycles.

Stenohaline vs. euryhaline characteristics: Deep-sea and mesopelagic fish species generally encounter stable salinity environments and tend to be stenohaline (narrow salinity tolerance). However, alfonsino are found across broad geographic ranges and depth strata, suggesting some physiological flexibility. Marine teleosts in general are well-adapted to oceanic salinity (\~35 psu) through osmoregulation.

What Information IS NOT Available:

No studies specifically examine alfonsino salinity tolerance limits or osmoregulatory capacity. However, this gap is not critical for vulnerability assessment because alfonsino habitat characteristics make significant salinity exposure highly unlikely.

Projected salinity changes at 300-1200m depths in the SIOFA region under climate scenarios are not well resolved in models, but this is low priority given the stability of deep water masses and small magnitude of expected changes.

Synthesis and Rating Justification:

The GREEN rating indicates low applicability of salinity hazards to alfonsino. The species' depth range and geographic distribution in the open ocean away from freshwater influences means exposure to significant salinity changes is minimal. Mesopelagic and bathyal waters maintain stable salinity over time and space compared to surface waters.

While we lack species-specific salinity tolerance data, this is not a priority research gap because: (1) habitat characteristics indicate low exposure, (2) marine teleosts generally tolerate oceanic salinity well, and (3) projected climate-driven salinity changes at depth

are small magnitude. Resources are better directed toward hazards with demonstrated exposure and higher uncertainty about sensitivity (temperature, oxygen, acidification).

H5: Deoxygenation (OMZ Expansion)

What Information IS Available:

Indian Ocean deoxygenation: The IO Climate Summary documents that the Indian Ocean is experiencing measurable deoxygenation, particularly in the northern regions where intense OMZs already exist (Arabian Sea, Bay of Bengal). The IO Climate Summary documents a complex three-regime response of Indian Ocean OMZs to climate forcing: expansion of outer low-oxygen volumes, contraction of the most intense suboxic core waters, and spatial redistribution of intermediate oxygen volumes — rather than simple uniform expansion. Warming reduces oxygen solubility and strengthens stratification, reducing ventilation of intermediate waters.

The southern Indian Ocean shows less dramatic deoxygenation than northern regions due to better ventilation from Southern Ocean water masses, but subtle declining trends are still detected. Mesopelagic depths (200-1000m) are particularly vulnerable to deoxygenation because they sit below the well-oxygenated surface mixed layer but above the deep circulation that maintains bottom water oxygen levels.

Seamount ecosystems and oxygen: Seamounts can experience localised oxygen dynamics depending on current patterns. Upwelling on seamounts may deliver well-oxygenated water, while some seamounts in OMZ regions show oxygen depletion. No specific studies address oxygen conditions at SIOFA seamounts where alfonsino aggregate.

What Information IS NOT Available:

No data exist on alfonsino oxygen requirements, tolerance limits, or responses to hypoxia. We do not know the minimum oxygen concentration alfonsino can tolerate, whether they exhibit hypoxia avoidance behaviour, or how sub-lethal hypoxia affects growth, reproduction, or feeding.

Comparative data from related species (Berycidae family) are also lacking. Unlike tuna or billfish where oxygen physiology is well-studied due to their high metabolic demands, mesopelagic demersal species like alfonsino have received little physiological research attention.

The vertical distribution of alfonsino relative to oxygen profiles is not systematically studied. Do alfonsino select depth strata based partly on oxygen availability? Do they avoid areas where the OMZ intersects seamount habitats? Field studies linking alfonsino catch rates or distribution to oxygen conditions are absent.

Projected changes in oxygen concentrations specifically at 300-1200m depths in the south-central Indian Ocean under climate scenarios are not well resolved. Regional ocean models do not provide high-resolution oxygen projections at seamount scales relevant to alfonsino habitat.

Synthesis and Rating Justification:

The AMBER rating reflects moderate-high concern with significant uncertainty. Deoxygenation is documented in the Indian Ocean (IO Climate Summary) and poses a plausible threat to mesopelagic species, but we cannot quantify risk without oxygen requirement data for alfonsino.

Compared to highly active pelagic species (tuna, billfish) with high oxygen demands, alfonsino may be less immediately vulnerable given their demersal lifestyle and presumably lower metabolic rates. However, OMZ expansion could still: (1) compress vertical habitat if hypoxic waters expand into their depth range, (2) reduce suitable seamount habitat if oxygen declines, (3) affect prey availability if zooplankton and small fish are displaced by hypoxia.

The southern Indian Ocean is currently well-oxygenated relative to northern regions, providing some buffer. However, long-term deoxygenation trends are concerning even if absolute oxygen levels remain above critical thresholds for now.

This is a HIGH PRIORITY research gap requiring: (1) laboratory experiments to establish alfonsino oxygen tolerance, (2) field studies linking distribution to oxygen profiles, (3) monitoring oxygen conditions at key seamount fishing grounds. Cannot be fully addressed through expert elicitation without empirical data foundation. The AMBER rating could shift to RED if research reveals high sensitivity and substantial OMZ expansion into alfonsino habitat, or to GREEN if species proves tolerant and habitat remains well-oxygenated.

H6: Wind Stress Changes

What Information IS Available:

Monsoon-driven wind systems: The IO Climate Summary identifies the southwest monsoon as a key driver of seasonal chlorophyll-a patterns in major Indian Ocean upwelling areas. Wind stress drives coastal and open-ocean upwelling that delivers nutrients to surface waters, supporting primary production. The seasonal reversal of monsoon winds (southwest in boreal summer, northeast in boreal winter) creates pronounced seasonal cycles in productivity across much of the northern and central Indian Ocean. The southwest monsoon period (June-September) generates strong upwelling in the western Indian Ocean, Arabian Sea, and Somali Coast regions.

Climate change impacts on wind patterns: IO Climate Summary discussed projected changes to monsoon intensity and timing under climate scenarios. Warming may alter atmospheric circulation patterns affecting monsoon strength, onset timing, and duration. Some projections suggest intensification of monsoon rainfall but changes to wind stress are less certain and vary regionally. Models show potential for weakening of some wind-driven circulation features while others may strengthen, with high inter-model variability indicating substantial uncertainty.

Upwelling dynamics and productivity: The IO Climate Summary examines how wind-driven upwelling influences primary productivity across the Indian Ocean. They documented that weakening of wind-driven upwelling in some regions contributes to productivity declines as nutrient delivery to surface waters decreases. The study found that regions heavily dependent on monsoon-driven upwelling showed the strongest productivity-wind stress relationships. However, regional variation is substantial - some areas may experience strengthened upwelling while others weaken, depending on how atmospheric circulation patterns shift.

Seamount current interactions: Although not specific to climate change, the oceanographic literature establishes that seamounts interact with prevailing currents to generate localised upwelling, current acceleration around seamount flanks, and retention zones in lee areas. Wind stress influences the strength of regional currents that interact with seamount topography, potentially affecting local productivity and prey aggregations. Enhanced mixing and nutrient injection at seamounts depends partly on current velocity, which is influenced by wind-driven circulation patterns.

What Information IS NOT Available:

No studies examine direct effects of wind stress on alfonsino behaviour, distribution, or physiology. As a demersal species living at 300-1200m depths, alfonsino are physically buffered from direct wind effects unlike surface-oriented pelagic species that may be displaced by wind-driven currents or experience wave action impacts. Whether alfonsino can detect wind-forced oceanographic changes (through temperature, current, or prey shifts) and respond behaviourally is unknown.

The cascading effects of altered wind patterns on mesopelagic food webs and alfonsino prey availability are not quantified. While we understand that wind drives upwelling and surface productivity, the translation of surface productivity changes to mesopelagic depths through vertical carbon flux and trophic pathways is complex and poorly characterised for seamount ecosystems. Mesopelagic consumers like alfonsino depend on the vertical flux of particulate organic matter and diel migrating zooplankton, both of which may be affected by surface productivity changes, but these linkages are not well studied.

Seamount-scale wind-current-upwelling interactions under changing climate are not modelled. Whether seamounts in the south-central Indian Ocean will experience enhanced or reduced local productivity under altered wind regimes depends on fine-scale oceanographic processes (Taylor column formation, trapped waves, lee eddy generation) not resolved in regional climate models. The outcome depends on whether weakened or strengthened regional currents enhance or diminish seamount productivity mechanisms.

Species-specific responses of alfonsino to prey field changes driven by wind pattern shifts are entirely unknown. We cannot predict whether alfonsino can compensate for altered prey availability through dietary shifts (switching prey species), foraging behaviour changes (expanding foraging range or depth), or habitat adjustments (moving between seamounts). The flexibility of alfonsino foraging ecology under environmental change has not been studied.

Synthesis and Rating Justification:

The AMBER rating reflects moderate applicability with indirect exposure pathways and substantial uncertainty. Wind stress changes are well-documented in Indian Ocean climate projections, and the linkages between wind, upwelling, and primary productivity are established. However, alfonsino's deep demersal habitat provides substantial buffering from direct wind effects - they do not experience wind-driven surface displacement, wave exposure, or direct wind-forced temperature changes that affect surface and near-surface species.

The primary mechanism of impact would be indirect through food web disruption. Altered wind patterns could affect: (1) seasonal productivity cycles that cascade down to influence mesopelagic prey availability with time lags, (2) vertical flux of organic matter to mesopelagic depths changing food supply, (3) regional current patterns affecting larval dispersal and population connectivity, (4) seamount-scale oceanography that maintains productive foraging habitat through current-topography interactions.

Compared to surface-oriented pelagic species (tunas, billfishes, flying fish), alfonsino are likely less immediately vulnerable to wind stress changes. The depth of their habitat (300-1200m) means they do not experience wind-driven mixed layer dynamics or wave action impacts. Their association with geographically fixed seamounts also means they cannot actively follow shifting wind-driven frontal systems the way pelagic species might.

However, they remain fundamentally dependent on food webs supported by wind-driven productivity. If wind pattern changes substantially reduce surface productivity in the south-central Indian Ocean or alter the efficiency of vertical carbon export to mesopelagic depths, alfonsino could experience food limitation affecting growth, reproduction, and population productivity.

The rating is AMBER rather than GREEN because the indirect pathways create moderate uncertainty and we lack species-specific response data. We have good understanding of regional wind-productivity linkages but poor understanding of how these propagate to mesopelagic depths specifically at seamount ecosystems. The rating is not RED because we do have substantial regional oceanographic knowledge even if species-specific responses remain uncertain. Understanding alfonsino diet flexibility and prey field dynamics at seamounts would help resolve uncertainty about food web pathway vulnerabilities.

H7: Ocean Current Changes

What Information IS Available:

Major Indian Ocean current systems: The Indian Ocean circulation is dominated by monsoon-driven reversing currents in the north (including the Somali Current and monsoon gyres), the South Equatorial Current flowing westward across the tropical basin, subtropical gyres in the south, and boundary currents along continents (Agulhas, Leeuwin, East African Coastal Current). The IO Climate Summary discusses how climate change may affect current strength, positions, and stability through altered wind patterns, ocean density gradients, and ocean heat content distribution. Warming-induced stratification may weaken some current systems while others could intensify.

Climate mode influences: The El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) drive interannual variability in Indian Ocean currents, temperature, and productivity. During positive IOD events, the western Indian Ocean warms while the eastern basin cools, reversing during negative IOD. ENSO also influences Indian Ocean conditions through atmospheric teleconnections and oceanic wave propagation.

Lehodey & Grandperrin (1996) demonstrated that ENSO-driven oceanographic variability in the Pacific affected alfonsino growth rates with a 7.5-month lag at 23-25°S. They measured growth rate variations through otolith annuli width, finding strong correlations between temperature in the 0-500m layer and growth increments. This establishes that alfonsino populations can be sensitive to large-scale climate modes operating through ocean circulation changes.

Current changes and connectivity: Ocean currents are primary drivers of larval dispersal distances and directions, influencing population connectivity and genetic structure. For seamount-associated species, currents connecting seamount complexes are critical for maintaining metapopulation structure. The direction, speed, and consistency of currents determine whether larvae released from one seamount can successfully reach others or are advected away from all suitable habitat. Changes to current patterns under climate change could affect recruitment dynamics, population resilience, and effective population size.

Nutrient delivery mechanisms: Currents transport nutrients horizontally and interact with seafloor topography to generate upwelling and mixing. At seamounts, current-topography interactions create Taylor columns (trapped rotating water masses), retention zones in lee areas, and enhanced productivity through nutrient injection. The formation and stability of these features depends on current speed and direction. Changes to regional current patterns could alter these local oceanographic features that make seamounts productive foraging habitat.

What Information IS NOT Available:

No studies document Indian Ocean alfonsino larval dispersal patterns or duration. We do not know larval development time (days to weeks? months?), pelagic larval depth distribution (surface? subsurface?), swimming capability (passive drifters? active swimmers?), or settlement behaviour (random? selective for specific seamount features?). Without this fundamental information, we cannot predict how current changes would affect dispersal distances, connectivity between seamount populations, or recruitment success. Even basic questions like whether larvae disperse 10km, 100km, or 1000km cannot be answered.

The influence of ENSO and IOD on Indian Ocean alfonsino populations is entirely unknown. While Lehodey & Grandperrin (1996) showed clear ENSO effects on Pacific alfonsino growth, whether Indian Ocean populations respond to IOD or ENSO teleconnections is unstudied. Do growth rates fluctuate with climate modes? Does recruitment vary with oceanographic conditions driven by IOD? Do distributions shift during extreme climate mode events? These questions are unanswered.

Projected changes to current patterns at seamount scales in the south-central Indian Ocean are not available from climate models. Regional ocean projections focus on basin-scale circulation features (subtropical gyre strength, boundary current transport, monsoon current reversals) but do not resolve currents at 1-10km scales relevant to individual seamounts or seamount chains. The fine-scale currents that determine seamount productivity and larval connectivity operate below the resolution of current climate model outputs.

Critical current thresholds for maintaining seamount productivity are unknown. At what current speed or direction do seamounts cease to generate profitable foraging conditions for alfonsino? How much change in current strength can populations accommodate before recruitment connectivity fails or local productivity collapses? Understanding these thresholds is essential for predicting climate change impacts but requires detailed seamount-scale oceanographic studies combined with biological monitoring.

Adult movement patterns relative to currents are not studied. Do adult alfonsino use currents for seasonal or ontogenetic migrations between seamounts? Do they actively maintain position against currents or are they displaced with current flow? Are their

foraging ranges constrained by current patterns? These behavioural unknowns limit our ability to predict adult distributional responses to changing circulation. If alfonsino actively navigate using current cues, disruption of familiar current patterns could be disorienting; if they are passive with currents, they might be displaced from optimal habitat.

Synthesis and Rating Justification:

The AMBER rating indicates moderate concern with substantial uncertainty about exposure pathways and species responses. Ocean currents influence multiple processes relevant to alfonsino ecology: larval dispersal and recruitment, nutrient delivery to seamounts, regional prey distribution, and the oceanographic features that make seamounts productive aggregation sites. Climate-driven current changes are projected for the Indian Ocean — the IO Climate Summary quantifies an 11–23% weakening of the Agulhas Current and a 26% reduction in the Indonesian Throughflow, though details at relevant spatial scales are poorly resolved.

The Pacific evidence from Lehodey & Grandperrin (1996) provides critical proof-of-concept that alfonsino populations respond to oceanographic variability linked to large-scale circulation patterns. The demonstrated correlation between ENSO-driven temperature changes and growth rates suggests Indian Ocean populations may similarly respond to IOD-driven or ENSO-influenced circulation changes. However, the specific mechanisms (temperature effects on metabolism? prey availability? both?) remain unclear, and whether Indian Ocean climate modes have comparable effects is unknown.

Early life stages are likely most vulnerable to current changes. Larval dispersal is the critical process determining recruitment patterns and population connectivity. If climate change alters current speeds, directions, or consistency such that larvae no longer successfully disperse between seamounts or settlement areas shift beyond historical ranges, population structure could be fundamentally disrupted. Seamount populations could become isolated if connecting currents weaken or larvae could be advected away from all suitable habitat if currents strengthen or change direction.

The seamount association creates vulnerability because currents must deliver larvae back to discrete suitable habitat. Pelagic species can settle almost anywhere within broad environmental envelopes, but alfonsino larvae must find seamounts. Small changes in current patterns could determine whether larvae encounter seamounts or are lost to unsuitable habitat. This contrasts with continental slope species where suitable habitat is more continuous.

The rating is not GREEN because we lack species-specific data on the most vulnerable life stage (larval ecology), dispersal patterns, and sensitivity to current-driven environmental variables. Without knowing larval duration or behaviour, we cannot confidently assess how vulnerable connectivity is to current changes. The rating is not

RED because we have good regional oceanographic understanding, proxy evidence from Pacific populations suggesting potential sensitivity, and established principles linking currents to seamount ecosystems.

AMBER appropriately acknowledges moderate concern requiring targeted research to resolve uncertainty. HIGH PRIORITY gaps include: (1) larval ecology studies establishing development time and depth distribution, (2) genetic connectivity analyses revealing current population structure and inferring dispersal patterns, (3) time series analyses correlating alfonsino population metrics with IOD/ENSO indices to detect climate mode sensitivity. These studies would substantially improve our ability to assess current change vulnerabilities.

Part 2: Sensitivity and Adaptative Capacity Indicators

Part 2 evaluates the biological and behavioural characteristics that determine how alfonsino 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 temperature proxy: Shotton (2016) characterized alfonsino as a circumglobal species occupying depth ranges of 25–1,300m, commonly aggregating over rocky substrates across temperate and subtropical waters. FishBase documents alfonsino occurring from 45°N to 43°S across Atlantic, Pacific, and Indian Oceans, suggesting tolerance of a broad temperature range. This circumglobal subtropical distribution indicates the species can occupy waters across approximately 88 degrees of latitude, encountering substantial temperature variation. The depth range of 25-1300m (typically 400-600m; SIOFA 2025) provides additional thermal buffering, as mesopelagic depths experience less extreme temperature fluctuations than surface waters.

Temperature-growth relationship: Lehodey & Grandperrin (1996) provided the only direct evidence of alfonsino temperature sensitivity. Working with New Caledonian populations at 500-900m depths on seamounts (23-25°S), they demonstrated that growth rates respond to temperature variability in the 0-500m water column. Otolith annuli width

measurements revealed growth rate variations correlated with ENSO-driven temperature changes with a 7.5-month lag. El Niño events (warmer temperatures) increased growth rates, while La Niña events (cooler temperatures) reduced growth rates. This establishes that alfonsino metabolism and somatic growth are temperature-sensitive, with oceanographic variability affecting population productivity.

Metabolic flexibility: Saavedra et al. (2015) measured lactate dehydrogenase (LDH) activity at 190.2 µmol/g tissue in alfonsino, suggesting metabolic enzyme systems capable of functioning across varying conditions. LDH is involved in anaerobic metabolism and can indicate physiological flexibility, though this measurement alone doesn't define thermal tolerance limits.

Regional warming exposure: Dalpadado et al. (2023) documented that the Indian Ocean is warming faster than any ocean except the Arctic, with SST projections of +1.7 to +3.8°C by 2100 depending on emission scenarios. Critically for alfonsino, Azarian et al. (2023) demonstrated that marine heatwaves penetrate below the surface mixed layer to 100-500m depths in the Southern Indian Ocean, directly overlapping alfonsino's primary depth range (400-600m). This establishes that thermal changes are not limited to surface waters but affect the mesopelagic habitat where alfonsino aggregate on seamounts.

What Information IS NOT Available:

No experimental determination of thermal tolerance limits: Critical thermal maximum (CTmax) and minimum (CTmin) have not been determined for alfonsino from any population. We do not know the upper temperature threshold that causes mortality, reproductive failure, or cessation of feeding. Without CTmax data, we cannot assess whether projected warming (+1.7-3.8°C; IO Climate Summary) will push temperatures beyond tolerable limits or whether alfonsino have sufficient thermal safety margins.

Optimal temperature range undefined: While Lehodey & Grandperrin (1996) showed growth responds to temperature variability, they did not identify the optimal temperature for maximum growth rates. We don't know if alfonsino growth plateaus above certain temperatures, whether there's a thermal optimum curve, or how growth declines if temperatures become too warm or cool. The demonstrated correlation doesn't reveal the shape of the thermal performance curve.

No Indian Ocean-specific thermal data: All temperature-related studies (Lehodey & Grandperrin 1996, Saavedra et al. 2015) come from Pacific populations. Indian Ocean alfonsino may experience different thermal regimes and could have locally adapted thermal tolerances. Water temperatures at 400-600m depths in SIOFA Convention Area are not well-characterized under current conditions or projected future scenarios at seamount scales.

Thermal acclimation capacity unknown: We don't know whether alfonsino can physiologically acclimate to warmer temperatures over seasonal or longer timescales. Can they adjust their thermal tolerance through phenotypic plasticity? What is the acclimation time required? Are there energetic costs to maintaining function at higher temperatures that reduce growth or reproduction even if survival is possible?

Life stage thermal sensitivity not characterized: Early life stages (eggs, larvae, juveniles) often have narrower thermal tolerances than adults. Spawning may require specific temperature windows. We lack data on thermal requirements and tolerances across alfonsino's complete life cycle.

Uncertain adaptation potential: While the broad distribution suggests historical ability to occupy varied thermal environments, capacity for evolutionary adaptation to rapid anthropogenic warming is unknown. Generation time of 6-8 years to maturity (potentially 50-70 years longevity; SIOFA 2023 age validation) means evolutionary responses would be slow. Is there standing genetic variation for thermal tolerance that could enable selection responses?

Synthesis and Rating Justification:

AMBER rating reflects available proxy evidence of thermal sensitivity balanced against critical data gaps. The framework question can be partially answered:

Temperature tolerance: The broad distributional range (45°N-43°S; FishBase) provides reasonable proxy evidence for moderate thermal tolerance. Circumglobal subtropical distribution suggests alfonsino can tolerate temperature variation across \~88° latitude. Depth distribution (400-600m) provides thermal buffering compared to surface-dwelling species, as mesopelagic waters experience more stable temperatures. However, this is indirect evidence---actual CTmax/CTmin remain unknown.

Adaptation to increased temperature: The demonstrated temperature-growth relationship (Lehodey & Grandperrin 1996) indicates alfonsino respond to thermal variability through altered growth rates, suggesting temperature affects metabolism and energy allocation. However, whether this represents problematic vulnerability or adaptive flexibility cannot be determined without knowing optimal temperature ranges and tolerance limits. The 7.5-month lag suggests population-level responses operate through food web-mediated pathways (temperature affects prey availability which affects alfonsino growth) rather than direct thermal physiology.

The depth distribution provides some buffering: Azarian et al. (2023) showed marine heatwaves penetrate to 500m but warming may be attenuated at depth compared to surface. The Azarian et al. (2023) finding that MHWs penetrate to 500m depth is retained with its original attribution. The IO Climate Summary documents the transition to near-perpetual MHW conditions but does not reproduce the specific 500m depth-

penetration figure. This claim requires either verification against the IO Climate Summary or retention of the original Azarian et al. (2023) source.

However, alfonsino's seamount association means if warming occurs at specific seamount locations, distributional responses are constrained by availability of suitable alternative seamount habitat within dispersal range. Metabolic enzyme data (Saavedra et al. 2015) suggests physiological flexibility but LDH activity alone doesn't define thermal tolerance. This enzyme's role in anaerobic metabolism may be more relevant for oxygen tolerance than temperature tolerance.

Not GREEN because: We lack direct experimental data on thermal tolerances from any population, particularly Indian Ocean populations. Cannot confidently state whether projected warming exceeds tolerance limits. Distribution proxy is reasonable but indirect.

Not RED because: Broad distribution provides meaningful proxy for thermal tolerance. Temperature-growth relationship establishes sensitivity exists and direction of response. Depth distribution context available. Framework question partially answerable with caveats.

HIGH PRIORITY research need: Experimental determination of CTmax/CTmin for Indian Ocean alfonsino across life stages. Define optimal thermal ranges for growth and reproduction. Quantify acclimation capacity and energetic costs of thermal stress. Model thermal exposure at SIOFA seamounts under climate scenarios.

S2;A3: Mobility (Ability to Move to New Locations)

What Information IS Available:

Life form and habitat association: FishBase classifies alfonsino as benthopelagic, indicating association with the seafloor but also using the water column. Lehodey et al. (1994) documented strong seamount association, with commercial catches concentrated over seamount topography rather than dispersed across open ocean habitat. This seamount association is consistent across the global range and specifically confirmed for SIOFA waters (SIOFA 2025, SC-10-14-Rev1).

Evidence of movement capacity: Lehodey et al. (1997) documented spawning migrations in New Caledonian waters, where alfonsino aggregate on specific seamounts for reproduction. This demonstrates capacity for directed movement between foraging and spawning areas, though the distances involved were not quantified. The fact that populations form spawning aggregations on particular seamounts implies ability to navigate to specific locations rather than being entirely sedentary.

Spatial distribution pattern: Brouwer et al. (2023) documented alfonsino catches from Cook Islands vessels across a wide spatial distribution in SIOFA waters, with two main

areas of catch density (30–60°E and east of 80°E), indicating multi-seamount occupation. SIOFA (2025) reported alfonsino catches across multiple seamounts in Subareas 2-4 of the south-central Indian Ocean. This indicates either: (1) populations occupy multiple seamounts simultaneously, (2) individuals move between seamounts, or (3) larvae disperse between seamounts maintaining connected populations.

Genetic connectivity evidence: Middleton et al. (2023) initiated genetic stock structure analysis across SIOFA seamounts. The study's design (sampling from multiple seamount locations) aims to determine whether populations are genetically distinct (indicating limited gene flow/movement) or show connectivity (indicating movement or larval dispersal). Preliminary work suggests genetic sampling has occurred but comprehensive results characterizing connectivity patterns are not yet published.

Larval dispersal potential: Mundy (1990) noted an extended larval period for alfonsino, though specific duration was not quantified. Extended pelagic larval duration (PLD) generally enables longer-distance dispersal via ocean currents. If larvae remain in the plankton for weeks to months, passive transport could connect populations across 10s to 100s of kilometers. However, larval depth distribution, swimming capability, and settlement selectivity are unknown.

Depth range flexibility: The documented depth range of 25-1300m (FishBase), though typically 400-600m (SIOFA 2025), demonstrates alfonsino can occupy a broad vertical habitat range. This depth flexibility could enable vertical redistribution in response to changing conditions (e.g., moving deeper if surface layers warm excessively), though whether populations actually make such shifts is unobserved.

What Information IS NOT Available:

No tagging or tracking studies: No alfonsino have been tagged to directly observe movement patterns, home ranges, migration distances, or site fidelity. We cannot quantify how far individuals move between seamounts, whether they exhibit seasonal migrations, or if they remain on a single seamount throughout their lives. The spawning migrations noted by Lehodey et al. (1997) demonstrate movement occurs but distances and frequencies are undocumented.

Movement rates and triggers unknown: If environmental conditions degrade at a seamount (warming, deoxygenation, reduced prey), do alfonsino actively relocate? How quickly can populations shift to new locations? What environmental cues trigger movement versus remaining in degraded habitat? Can adults navigate between seamounts or is connectivity maintained primarily through larval dispersal?

Habitat selectivity not characterized: When seeking new habitat, what features do alfonsino require? Any seamount with suitable depth range? Specific topographic characteristics (summit depth, slope, size)? Particular oceanographic conditions (current

patterns, temperature, productivity)? Without understanding habitat requirements, we cannot identify which seamounts could serve as suitable destinations if current locations become unsuitable.

Dispersal distances undefined: Critical question for climate adaptation: How far can alfonsino move (either as adults or larvae) to reach alternative suitable habitat? If the nearest suitable seamount is 50km away, can populations reach it? What about 200km? 500km? Both adult movement capacity and larval dispersal distances are completely unknown for Indian Ocean populations.

Cost of movement not quantified: Does relocating between seamounts impose energetic costs affecting growth or reproduction? Do individuals that attempt long-distance movements suffer higher mortality? Even if physically capable of movement, are there fitness consequences that limit effective mobility?

Genetic connectivity incomplete: Middleton et al. (2023) has begun genetic work but comprehensive results are not available in that report. Are SIOFA seamount populations a single panmictic stock with high gene flow, multiple distinct stocks with limited connectivity, or a metapopulation with intermediate connectivity? High connectivity would suggest good dispersal/movement capacity; low connectivity would suggest limited mobility and isolation vulnerability.

Synthesis and Rating Justification:

AMBER rating reflects evidence of movement capacity but major uncertainties about extent and limitations. The framework question can be partially answered:

Ability to move: Evidence demonstrates alfonsino are not completely sedentary. Spawning migrations (Lehodey et al. 1997) prove directed movement occurs. Presence across multiple SIOFA seamounts (SIOFA 2025) indicates populations occupy spatially separated locations, suggesting either movement or effective larval dispersal maintains presence across the region. Extended larval period (Mundy 1990) provides mechanism for longer-distance passive dispersal.

However, seamount association fundamentally constrains mobility compared to pelagic species. Alfonsino cannot simply track optimal conditions across continuous habitat---they require discrete seamount features. If climate change makes a seamount unsuitable, movement is only effective if: (1) alternative suitable seamounts exist within dispersal/movement range, (2) individuals can successfully navigate to new locations, and (3) new locations have sufficient habitat and food to support immigrant populations.

The depth range flexibility (25-1300m, typically 400-600m) suggests capacity for vertical redistribution (e.g., moving deeper if shallower depths become too warm), but this requires suitable habitat at deeper depths on the same seamount. Not all seamounts may have appropriate depth range.

Genetic connectivity (Middleton et al. 2023) is critical missing piece. If genetic differentiation is low across SIOFA seamounts, this indicates effective gene flow through either adult movement or larval dispersal, suggesting good mobility. If genetic structure is strong, populations may be effectively isolated with limited capacity for spatial redistribution in response to local environmental changes.

Comparison to other seamount species: Many seamount-associated fishes show strong site fidelity with limited adult movement but connectivity maintained through larval dispersal. If alfonsino follow this pattern, climate adaptation through movement depends heavily on larval survival during extended pelagic phase and successful settlement at new seamounts---processes vulnerable to ocean warming, acidification, and changing current patterns.

Not GREEN because: Direct movement data (tagging, telemetry) absent. Dispersal distances unknown. Cannot confidently quantify ability to reach alternative locations if needed.

Not RED because: Evidence demonstrates movement occurs (spawning migrations). Spatial distribution across multiple seamounts suggests mobility or effective dispersal. Extended PLD provides mechanism. Framework question partially answerable.

HIGH PRIORITY research: Acoustic or satellite tagging to quantify adult movement patterns and home ranges. Complete genetic connectivity analysis (Middleton et al. 2023). Larval ecology studies defining PLD, dispersal distances, and settlement selectivity. Habitat suitability modeling identifying potential climate refugia within dispersal range.

S3;A2: Productivity

What Information IS Available:

Late sexual maturity: Lehodey et al. (1997) documented sexual maturity at 6-8 years for New Caledonian alfonsino populations. This is confirmed as representative for the species across multiple studies. Guerrero & Arana (2009) reported similar age-at-maturity estimates for Chilean populations. Late maturity is a K-selected trait associated with low population productivity---the longer the time to first reproduction, the slower populations can grow or recover from depletion.

Longevity is uncertain (major implications): Traditional ageing using whole otoliths suggested maximum ages of 10-25 years. However, the SIOFA Age Validation Study (2023) applied radiocarbon dating to the congener Beryx decadactylus and revealed longevity of 50-70 years---3 to 5 times higher than previous estimates. If B. splendens shares similar longevity (highly likely given taxonomic relatedness and similar ecology),

this dramatically affects productivity assessment. A species living 50-70 years with maturity at 6-8 years has fundamentally different population dynamics than one living 10-25 years. Generation time becomes much longer, natural mortality rate much lower, and population growth rate much slower.

K-selected life history strategy: FishBase classifies alfonsino as having K-selected characteristics: late maturity, extended longevity, presumed low fecundity (though fecundity data are lacking), and slow growth. The climate vulnerability score of 58/100 (High) reflects these traits. K-selected species have low intrinsic population growth rates and are vulnerable to overfishing and environmental perturbations because populations recover slowly from declines.

Temperature effects on growth and productivity: Lehodey & Grandperrin (1996) demonstrated that growth rates respond to temperature variability through ENSO cycles. Otolith annuli width showed El Niño events (warmer) increased growth while La Niña (cooler) reduced growth, with a 7.5-month lag. This establishes that population productivity is sensitive to temperature and oceanographic conditions. However, the demonstrated relationship shows growth variability under natural temperature fluctuations (±1-2°C), not responses to sustained directional warming of +1.7-3.8°C (IO Climate Summary).

Food web-mediated productivity impacts: The 7.5-month lag between temperature and growth (Lehodey & Grandperrin 1996) suggests productivity responses operate through food web pathways---temperature affects prey availability which affects alfonsino growth---rather than direct physiological effects. The IO Climate Summary confirms a general long-term productivity decline (20% phytoplankton reduction over six decades; −0.60% per year surface chlorophyll trend). If surface productivity declines cascade to mesopelagic prey populations, alfonsino productivity would decline through food limitation even if direct thermal effects are tolerable.

What Information IS NOT Available:

Age validation not complete for Indian Ocean B. splendens: The Andrews (2023) radiocarbon study validated age for B. decadactylus, demonstrating the Berycidae family has been systematically underaged. However, this validation has not been explicitly conducted for B. splendens in the Indian Ocean. While it is reasonable to assume similar longevity given taxonomic relatedness and similar ecology, direct confirmation is lacking. This creates 10-25 years vs 50-70 years uncertainty fundamentally affecting productivity assessment.

Fecundity unknown: No studies quantify egg production per female, batch fecundity, spawning frequency per season, or how fecundity varies with female size/age. Without fecundity data, reproductive output cannot be estimated. Are large old females highly fecund (as in many fish), making age truncation from fishing particularly damaging to productivity? Or is fecundity relatively constant across adult sizes?

Natural mortality rate unknown: With longevity uncertain (10-25 years vs 50-70 years), natural mortality rate (M) cannot be estimated reliably. M is inversely related to longevity---if alfonsino live 50-70 years, M would be very low (\~0.02-0.04 year^{-1}). This affects population productivity profoundly. Low M means populations can sustain only low fishing mortality (F) before becoming overfished, and recovery from depletion takes many decades.

Population growth rate unquantified: Intrinsic population growth rate (r) depends on maturity age, longevity, fecundity, and juvenile survival---most of which are uncertain or unknown. Without r, we cannot estimate recovery time from depletion or assess whether populations can maintain productivity under changed environmental conditions. How many years to rebuild to 40% of unfished biomass? 20 years? 50 years? 100+ years?

Recruitment variability and environmental drivers: Do alfonsino populations exhibit strong recruitment pulses in favourable years and failures in poor years (like many fish), or is recruitment relatively stable? What environmental factors drive recruitment success? How would climate change affect recruitment variability and average recruitment levels?

Temperature-productivity relationship at projected warming levels: Lehodey & Grandperrin (1996) showed growth responds to ±1-2°C natural variability. Would sustained +1.7-3.8°C warming (IO Climate Summary) continue improving productivity, or would there be a thermal optimum beyond which productivity declines? Is the current temperature regime already near optimal, such that any warming reduces productivity? The demonstrated relationship doesn''t reveal the shape of the temperature-productivity curve at higher temperatures.

Climate impacts on reproductive success: Will warming affect spawning success, egg survival, or larval survival? Climate-driven changes to oceanographic conditions could disrupt spawning cues, alter larval dispersal patterns, or reduce larval food availability. These reproductive impacts on productivity are completely unstudied.

Synthesis and Rating Justification:

AMBER rating reflects available life history data indicating low productivity with critical uncertainties. Framework questions can be partially answered:

Species productivity (recovery potential): Shotton (2016) assessed alfonsino productivity as moderate globally, with biological characteristics rendering the species susceptible to overfishing in the absence of effective management—a conclusion consistent with life history parameters documented across ocean basins. Based on available data, alfonsino have low population productivity characteristic of K-selected species:

- Late maturity: 6-8 years (Lehodey et al. 1997) means delayed reproductive contribution
- Extended longevity: 50-70 years if Andrews (2023) B. decadactylus findings apply, though validation for B. splendens in Indian Ocean pending
- K-selected strategy: FishBase vulnerability score 58/100 reflects life history traits associated with slow population growth
- Low recovery rate: Populations would recover slowly from depletion---likely decades to century timescale if longevity is 50-70 years.

If longevity is 50-70 years (upper estimate), productivity is extremely low with generation time of \~30-40 years and natural mortality \~0.02-0.04 year^{-1}. Recovery from depletion would require 50-100+ years. Conversely, if longevity is 10-25 years (traditional estimates), productivity would be higher with faster recovery, though still slow relative to many commercial species. This uncertainty fundamentally affects productivity assessment.

Maintaining/improving productivity under warming: The evidence suggests likelihood of maintaining productivity is low, with possibility of declines:

- Temperature-growth relationship (Lehodey & Grandperrin 1996) demonstrates sensitivity, but direction of impact under sustained +1.7-3.8°C warming unknown
- The 7.5-month lag indicates food web-mediated effects---productivity depends on prey availability
- Indian Ocean productivity declining in warming years - warmer temperatures with lower surface chlorophyll.
- If surface productivity declines cascade to mesopelagic prey, alfonsino productivity likely declines through food limitation
- No evidence suggests alfonsino can improve productivity under warming; at best they might maintain current levels if thermal conditions remain within tolerable range and prey populations are stable.

The K-selected strategy means alfonsino are poorly equipped for rapid adaptation to changing conditions. Long generation time (decades) limits evolutionary response speed. Low productivity means populations cannot quickly compensate for climate-driven mortality increases through elevated reproduction. If warming reduces growth rates, delays maturity further, or reduces reproductive success, productivity impacts

compound over the extended lifespan.

Not GREEN because: Age validation incomplete for Indian Ocean B. splendens creates 2-5× uncertainty in longevity. Fecundity unknown. Natural mortality and population growth rate unquantified. Temperature-productivity relationship only characterized for natural variability, not sustained directional warming. Cannot confidently project productivity under climate scenarios.

Not RED because: Maturity age well-documented (6-8 years). Longevity estimates available with caveats (10-25 years traditional; 50-70 years if B. decadactylus finding applies). K-selected strategy established. Temperature-growth relationship demonstrated. Framework questions partially answerable with substantial caveats.

CRITICAL PRIORITY research: Complete age validation for Indian Ocean B. splendens using radiocarbon dating (resolve 10-25 vs 50-70 years uncertainty---this fundamentally affects all productivity assessments). Quantify fecundity across female sizes/ages. Develop population growth model incorporating validated life history parameters. Quantify recruitment variability and environmental drivers. Define temperature-productivity relationship across full range of projected warming scenarios.

S4; A3: Distributional Range and Habitat Flexibility

What Information IS Available:

Large geographic range: FishBase documents alfonsino occurrence across all three major oceans (Atlantic, Pacific, Indian) from 45°N to 43°S latitude. This circumglobal subtropical distribution spanning approximately 88 degrees of latitude indicates the species can occupy extremely broad geographic ranges and environmental gradients. The species occurs in both hemispheres across multiple ocean basins, suggesting high dispersal capacity historically or ecological plasticity enabling colonisation of diverse regions. Brouwer et al. (2023) reported alfonsino catches concentrated on seamounts and plateaus at 1,000–2,000m depth along the Madagascar Ridge, Southwest Indian Ridge, and Broken Plateau, with fishing operations extending from 25°S southward

Depth range flexibility: The documented depth range of 25-1300m (FishBase) demonstrates substantial vertical habitat breadth, though populations typically concentrate at 400-600m depths (SIOFA 2025). This depth flexibility could enable vertical redistributions in response to changing conditions---for example, moving deeper if shallower depths warm excessively or experience oxygen depletion, or moving shallower if suitable prey or oceanographic conditions shift upward. The 1275m vertical range provides significant potential for depth-based climate refuge seeking.

Multiple seamount occupation: SIOFA (2025, SC-10-14-Rev1) reported alfonsino across multiple seamount features in Subareas 2-4 of the south-central Indian Ocean. Lehodey et al. (1994) documented similar multi-seamount occupancy in Pacific waters. This pattern indicates the species does not require a single unique seamount but rather utilises multiple features meeting habitat requirements. Alfonsino co-occur with orange roughy on many seamounts, suggesting overlap in habitat preferences but successful coexistence across numerous sites.

Habitat association pattern: While strongly associated with seamounts (Lehodey et al. 1994), alfonsino are classified as benthopelagic rather than strictly demersal, indicating they use both bottom-associated and midwater habitats. This may provide some flexibility compared to obligate demersal species that require direct seafloor contact. Annala & Sullivan (1996) documented alfonsino in both seamount and slope habitats in New Zealand waters, though seamounts support higher densities and commercial catches.

What Information IS NOT Available:

Historical range changes undocumented: Has alfonsino distribution shifted in response to past environmental variability or fishing pressure? We lack long-term baseline data on distribution patterns before intensive fishing. Did historical populations occupy different depth ranges, latitudes, or seamount types? Without baseline understanding, we cannot assess whether current distributions represent optimal habitat or fishing-depleted remnant populations.

Habitat requirements not quantified: What specific features make a seamount suitable for alfonsino? We lack quantitative understanding of habitat requirements: minimum/maximum depth of seamount summit, preferred slope angles, required current velocities, necessary prey densities, optimal temperature ranges. Without defining suitability criteria, we cannot predict which seamounts might serve as climate refugia or identify potential new habitats if distributional shifts occur.

Capacity for distributional shift unknown: Although the broad geographic range suggests historical ability to occupy varied environments, can contemporary populations actively shift distributions in response to climate change? Are adults capable of long-distance dispersal to new regions? Does colonisation depend entirely on larval dispersal? What is the timescale for range expansions or contractions---decades? centuries? The demonstrated capacity to occupy 88° of latitude across three oceans doesn’t necessarily translate to ability for rapid (\~decades) distributional shifts in response to anthropogenic climate change.

Depth preference drivers not understood: While alfonsino occur from 25-1300m, they concentrate at 400-600m (SIOFA 2025). Why this depth preference? Is it temperature-driven, prey availability, predation avoidance, oxygen levels, or other factors? Understanding depth preference mechanisms is critical for predicting whether vertical redistribution would occur under climate change and whether deeper or shallower depths could serve as refugia.

Limits to range not defined: What prevents alfonsino from occurring at higher latitudes (\>45°N, \>43°S)? Temperature tolerance limits? Lack of suitable seamount habitat? Competition with other species? Understanding range limits helps predict whether poleward range shifts are feasible under warming scenarios. Similarly, what limits equatorward distribution? Can tropical regions serve as source populations or are they unsuitable?

Indian Ocean distribution gaps: While SIOFA (2025) documents occurrence in Subareas 2-4, comprehensive surveys across the entire south-central Indian Ocean are lacking. Are there additional seamounts with suitable habitat that currently lack alfonsino populations (potential colonisation sites)? Or do alfonsino already occupy all suitable seamounts in the region (no additional habitat available for range expansion)?

Synthesis and Rating Justification:

AMBER rating reflects evidence of broad distributional range but uncertainty about capacity for active distributional shifts. Framework questions can be partially answered:

Distributional range coverage: Alfonsino demonstrably cover large areas---circumglobal subtropical distribution from 45°N to 43°S across Atlantic, Pacific, and Indian Oceans (FishBase). This is among the broadest distributions for seamount-associated species, indicating historical success occupying diverse environmental conditions across multiple ocean basins. The presence across numerous seamounts in SIOFA waters alone (Subareas 2-4; SIOFA 2025) shows regional distribution spans multiple distinct habitat features.

Habitat range adjustment: The depth range of 25-1300m demonstrates substantial vertical habitat breadth, suggesting some capacity to adjust to a range of depth habitats. The benthopelagic classification (vs strictly demersal) indicates use of both bottom and midwater environments, providing additional habitat flexibility. However, the strong seamount association fundamentally constrains habitat options---alfonsino cannot occupy continuous open ocean habitat but require discrete topographic features.

Capacity to change distributional patterns: This is the critical uncertainty. The broad current distribution demonstrates the species can occupy varied environments, but this

reflects evolutionary timescales and historical dispersal, not necessarily capacity for rapid (decadal) redistribution in response to climate change. Key limitations:

- Seamount constraint: Cannot track optimal conditions across continuous habitat; must move between discrete seamount features
- Adult mobility uncertain: Tagging data absent (see S2); unknown whether adults can undertake long-distance migrations to new regions
- Colonisation mechanism: If distributional shifts depend primarily on larval dispersal, success requires larvae encountering suitable seamounts within dispersal range and surviving extended pelagic period under changing ocean conditions
- Habitat requirements undefined: Cannot predict which new areas might be colonised without understanding what makes habitat suitable.

Historical broad distribution suggests ecological generalism and dispersal capacity enabled colonisation across ocean basins. However, contemporary populations may be more constrained by:

- fragmented seamount habitat compared to pre-fishing distributions,
- depleted population sizes reducing propagule pressure for colonisation,
- rapid anthropogenic climate change exceeding natural variability rates populations previously navigated, and
- simultaneous multiple stressors (warming + acidification + deoxygenation + fishing) not experienced historically.

Depth flexibility (25-1300m) provides pathway for vertical redistribution that doesn't require long-distance horizontal movement---if suitable deeper habitat exists on currently occupied seamounts, populations could shift downward in response to warming shallow waters. However, not all seamounts may have appropriate deeper habitat, and deeper waters may become oxygen-depleted (OMZ expansion) offsetting any thermal refuge benefit.

Not GREEN because: Historical broad range doesn''t confirm capacity for rapid contemporary distributional shifts. Habitat requirements not quantified preventing prediction of potential refugia or colonisation sites. Adult movement capacity unknown. Uncertainty whether depth flexibility translates to actual redistributions.

Not RED because: Demonstrable broad geographic and depth range. Multiple seamount occupation rather than single-site dependency. Framework question partially answerable based on current distribution patterns.

HIGH PRIORITY research: Habitat suitability modeling defining quantitative requirements (depth, temperature, prey, currents). Climate envelope modeling

identifying potential future suitable habitat. Long-term monitoring detecting distributional shifts. Habitat surveys identifying currently unoccupied suitable seamounts.

S5;A3: Environmental Cues Influencing Distribution

What Information IS Available:

Spawning site fidelity: Lehodey et al. (1997) documented that alfonsino form spawning aggregations on specific seamounts in New Caledonian waters, indicating directed movement to particular locations for reproduction. This site fidelity suggests environmental cues guide individuals to spawning grounds, though the specific cues (oceanographic, bathymetric, magnetic, chemical) were not identified. The fact that spawning occurs at predictable locations rather than randomly dispersed across all occupied seamounts implies environmental selection of spawning habitat.

Temperature influences growth: Lehodey & Grandperrin (1996) demonstrated alfonsino growth rates respond to temperature variability with 7.5-month lag. While this establishes temperature as an environmental cue affecting physiology and productivity, it doesn't directly address whether temperature cues spawning timing or location selection. The lag suggests food web-mediated effects rather than direct thermal cues driving behaviour.

Extended larval period: Mundy (1990) noted extended larval period without quantifying duration. If larvae remain pelagic for weeks to months, their distribution would be heavily influenced by ocean currents (environmental cue determining dispersal patterns) and potentially by temperature, salinity, or other cues affecting vertical distribution and settlement behaviour.

What Information IS NOT Available:

Spawning seasonality completely unknown for Indian Ocean: No studies document when alfonsino spawn in SIOFA waters. Is spawning seasonal (linked to environmental cycles) or year-round? If seasonal, what month(s)? The absence of spawning season data prevents assessment of environmental cue dependency. Many fish species time spawning to seasonal productivity pulses, temperature windows, or lunar cycles---we don't know if alfonsino follow similar patterns.

Environmental triggers for spawning unidentified: What cues initiate spawning? Candidates include:

- Temperature thresholds or rates of change (spring warming, autumn cooling)
- Lunar cycles (many species spawn around new/full moon)
- Photoperiod changes (day length as seasonal cue)

- Productivity pulses (prey availability for larvae)
- Current patterns (transport conditions for larvae)
- Internal endogenous rhythms (less dependent on external cues).

None of these have been studied for alfonsino. Without knowing triggering mechanisms, we cannot predict how climate change-altered environmental conditions would affect spawning timing or success.

Spawning habitat requirements undefined: What makes specific seamounts suitable for spawning versus foraging? Lehodey et al. (1997) showed spawning occurs at particular seamounts but didn''t characterize habitat features. Do spawning seamounts have distinct depth ranges, current patterns, temperature regimes, substrate types, or other attributes? Understanding spawning habitat requirements is critical for predicting climate change impacts---if warming makes spawning seamounts unsuitable, can alternative seamounts serve as spawning grounds?

Temperature tolerance for reproduction unknown: What temperature range permits successful spawning, fertilisation, and early development? Fish eggs and larvae often have narrower thermal tolerances than adults. If climate change shifts temperatures outside optimal reproductive windows, spawning success could decline even if adult survival is unaffected. We lack data on reproductive thermal limits.

Phenological plasticity unstudied: Can alfonsino adjust spawning timing if environmental cues shift? Climate change is altering seasonal cycles (earlier spring, later autumn, altered productivity timing). If spawning is tightly coupled to specific environmental windows, mismatches could develop between spawning timing and optimal larval feeding conditions (match-mismatch hypothesis). Can populations adapt spawning phenology over multi-generational timescales?

Distribution cues unknown: Beyond spawning, what environmental factors determine alfonsino distribution across seamounts for foraging? Temperature, prey density, current patterns, oxygen levels, competition? Do alfonsino actively select seamounts based on real-time environmental conditions or passively settle wherever larvae encounter suitable habitat? Understanding distribution determinants is essential for predicting redistributions under climate change.

Synthesis and Rating Justification:

RED rating reflects critical knowledge gaps preventing assessment of environmental cue influence. Framework questions cannot be adequately answered:

Level of environmental cue influence: We know alfonsino spawn at specific locations (Lehodey et al. 1997) and growth responds to temperature (Lehodey & Grandperrin 1996), proving environmental factors influence biology and behaviour. However, we cannot quantify the level of influence because:

- Spawning triggers unidentified---don't know if tightly coupled to specific cues or more flexible
- Distribution determinants unknown---cannot assess if movements track particular environmental conditions
- Relative importance of different cues undefined---is temperature primary driver? prey? currents?

Without understanding which environmental cues matter and how strongly they influence behaviour, we cannot predict climate change impacts. Species tightly coupled to specific environmental windows (narrow cue dependence) are highly vulnerable to climate-driven phenological shifts. Species with flexible cue responses or broader environmental tolerance (low cue dependence) are more resilient. Alfonsino could fall anywhere on this spectrum---we lack data to determine position.

Likelihood of adapting spawning under changed conditions: This question requires knowing:

(1) What current spawning cues are (unknown)
(2) How those cues will change under climate scenarios (partially known---temperature increasing, productivity declining, currents changing)
(3) Whether alfonsino can adjust to altered cues (unknown---no phenological plasticity studies)
(4) Whether alternative spawning habitats exist if current sites become unsuitable (unknown---spawning habitat requirements undefined).

The complete absence of Indian Ocean spawning data is particularly problematic. We don't know basic spawning biology (season, location characteristics, environmental associations) let alone adaptive capacity. The Pacific proxy data (Lehodey et al. 1997) confirms spawning aggregations occur but provides insufficient detail to assess climate vulnerability.

Comparison to other species: Many fish show strong environmental cue dependency for spawning---specific temperature windows, lunar cycles, seasonal timing. Climate change has caused spawning phenology shifts in numerous species, with consequences including:

- Match-mismatch problems: spawning shifts but larval prey timing doesn't, causing recruitment failures
- Spawning habitat loss: suitable temperature/conditions no longer occur at traditional spawning grounds

- Expanded vulnerability windows: earlier spawning exposes larvae to unsuitable conditions We cannot assess whether alfonsino face similar risks without baseline spawning ecology data.

Not AMBER because: Unlike other RED indicators where some proxy data exist, here we have virtually no information on spawning cues, environmental triggers, habitat requirements, or adaptive capacity. Cannot make even tentative assessment of climate vulnerability through this pathway.

CRITICAL PRIORITY research: Document spawning seasonality in SIOFA waters. Characterise spawning habitat environmental conditions (temperature, currents, depth, timing). Experimental studies testing spawning responses to temperature and other environmental variables. Long-term monitoring detecting spawning phenology changes. Identify which environmental cues trigger reproductive behaviour.

S6;A4: Reproductive Environmental Dependency and Spawning Strategy

What Information IS Available:

Spawning Strategy: Available evidence consistently confirms alfonsino are broadcast spawners across all studied populations:

- Egg characteristics: Pelagic, buoyant, free-floating eggs with no adhesion to substrate. Molecular confirmation (16S rRNA) definitively identifying collected eggs as *B. splendens*. Developmental stages from morula to pre-hatching observed floating in water column.
- Spatial dispersal patterns: Wide horizontal dispersal across spawning grounds. Vertical distribution 0-250m depth. Progressive diffusion from spawning sites as development proceeds, characteristic of external fertilization with no parental care.
- Geographic consistency: No evidence of nest-building, parental care, demersal eggs, or substrate attachment across populations in Japanese waters, Macaronesian archipelagos, Juan Fernández Archipelago, Azores, or New Zealand. This multi-basin consistency reinforces broadcast spawning classification.

Regional variation: Alfonsino are serial spawners reproducing in their normal habitat areas without extensive spawning migrations. Spawning timing varies markedly between regions, suggesting environmental cueing:

- Macaronesian archipelagos: September-March (Azores), March-June (Madeira), July-September (Canary Islands) -- demonstrating clear north-south latitudinal variation
- New Zealand: July-August spawning period
- Izu Islands, Japan: Concentrated spawning 02:00-06:00 (early morning), suggesting diel timing pattern
- Within-season patterns: Multiple developmental stages collected simultaneously indicates continuous or repeated spawning events throughout reproductive season rather than single synchronous spawning

Early life history dependencies

- Egg development: Buoyant eggs hatch after 1-8 days depending on environmental conditions (temperature-dependent development rate). Complete absence of parental care means eggs fully exposed to water column environmental variability.
- Larval phase: Extended pelagic larval phase of approximately 1 year before adopting demersal existence. Larvae widely distributed by surface currents, creating dependency on oceanographic transport to suitable settlement habitat.
- Population connectivity: Evidence suggests alfonsino populations may be associated with large oceanic eddy systems, with currents carrying eggs and

larvae between reproductive and 'vegetative' zones, and maturing fish migrating back. This implies dependency on large-scale circulation patterns for population connectivity.

Climate sensitivity: Demonstrated sensitivity of alfonsino growth rates to temperature and ENSO events suggests reproductive processes may also be influenced by oceanographic variability, though direct evidence of reproductive climate sensitivity is limited.

Dependency on environmental conditions for reproductive success:

- Alfonsino reproductive success is highly dependent on specific environmental conditions. Broadcast spawning with pelagic eggs, external fertilization, extended larval pelagic phase, and complete absence of parental care creates multiple critical dependencies on oceanographic conditions throughout early life history. Climate-driven changes to temperature, currents, stratification, or extreme events could affect fertilization success, egg and larval survival, dispersal patterns, and ultimately recruitment to adult populations.

- Fertilization success: External fertilization in open water requires precise oceanographic conditions. Temperature, current velocities, turbulence, and mixing patterns all affect whether eggs and sperm successfully encounter each other. Early morning spawning concentration (02:00-06:00 at Izu Islands) may represent behavioural optimization for favourable conditions, but eggs still entirely exposed to prevailing hydrodynamics. No mechanism exists to enhance fertilization when conditions are suboptimal.

- Egg survival: Free-floating pelagic eggs have zero parental protection. Temperature determines developmental rate (1-8 days to hatching). Oxygen, salinity, predation, and water column stability all influence survival. Vertical distribution to 250m means eggs occupy varying water masses with different environmental characteristics. Unsuitable conditions = mortality, with no capacity for parental rescue or behavioural avoidance.

- Larval transport and survival: Extended pelagic phase (\~1 year) creates absolute dependency on: (1) suitable water column conditions for survival, (2) encountering prey fields at correct developmental stages, (3) avoiding predators, (4) currents transporting larvae to appropriate settlement habitat. Hypothesis that alfonsino populations depend on large oceanic eddy systems (Alekseev et al. 1986) implies population viability requires stable circulation patterns maintaining connectivity between reproductive and juvenile zones.

- Spawning timing: Regional variation (September-March Azores, March-June Madeira, July-September Canary Islands, July-August New Zealand)

demonstrates environmental cueing, though specific triggers (temperature? photoperiod?) incompletely understood. Serial spawning over extended seasons requires consistently suitable conditions throughout reproductive period. Climate-driven shifts in thermal regimes could cause match-mismatch between larval emergence and optimal prey availability or transport conditions.

What information is NOT available

- Direct observations of spawning behaviour: All evidence is inferred from egg characteristics, distribution patterns, and larval ecology. No published visual documentation of gamete release, spawning aggregations, or fertilization events in the wild.
- Environmental triggers for spawning initiation: Mechanisms controlling spawning timing incompletely understood. Regional variation suggests temperature or photoperiod cueing, but specific threshold temperatures, lunar cycles, or other proximate cues not quantified.
- Fertilization success rates: No quantitative data on fertilization rates under varying oceanographic conditions. Relationship between temperature, current velocity, turbulence, and successful gamete encounter not empirically determined for alfonsino.
- Optimal environmental windows: Specific temperature ranges, oxygen levels, or salinity conditions that optimise egg survival and larval development unknown. Early morning spawning timing may indicate behavioural adaptation to favourable conditions but mechanism not elucidated.
- Larval survival determinants: Critical factors affecting survival during extended (\~1 year) pelagic larval phase not well documented. Prey field requirements, predation rates, and settlement cues largely unknown.
- Indian Ocean / SIOFA populations: No eggs or larvae documented from SIOFA Convention Area or Southern Indian Ocean to date. Spawning locations, timing, and early life history for Indian Ocean populations completely unknown. All evidence extrapolated from Pacific and Atlantic populations.
- Climate change impacts on reproduction: No empirical studies examining how changing ocean conditions (warming, stratification, acidification, deoxygenation) affect spawning success, egg development rates, larval survival, or recruitment. Potential impacts must be inferred from broadcast spawning theory and general climate sensitivity.
- Spawning aggregation characteristics: Spatial extent, density, and duration of spawning aggregations unknown. Whether spawning is concentrated or diffuse across seamount habitat not documented.
- Oceanographic thresholds: No data on limiting factors for successful reproduction -- minimum/maximum temperatures, critical current velocities, stratification conditions, or oxygen levels that prevent spawning or cause recruitment failure.

Dependency on environmental conditions for reproductive success:

Alfonsino reproductive success is highly dependent on specific environmental conditions. Broadcast spawning with pelagic eggs, external fertilization, extended larval pelagic phase, and complete absence of parental care creates multiple critical dependencies on oceanographic conditions throughout early life history. Climate-driven changes to temperature, currents, stratification, or extreme events could affect fertilization success, egg and larval survival, dispersal patterns, and ultimately recruitment to adult populations.

Fertilization success: External fertilization in open water requires precise oceanographic conditions. Temperature, current velocities, turbulence, and mixing patterns all affect whether eggs and sperm successfully encounter each other. Early morning spawning concentration (02:00-06:00 at Izu Islands) may represent behavioural optimization for favourable conditions, but eggs still entirely exposed to prevailing hydrodynamics. No mechanism exists to enhance fertilization when conditions are suboptimal.

Egg survival: Free-floating pelagic eggs have zero parental protection. Temperature determines developmental rate (1-8 days to hatching). Oxygen, salinity, predation, and water column stability all influence survival. Vertical distribution to 250m means eggs occupy varying water masses with different environmental characteristics. Unsuitable conditions = mortality, with no capacity for parental rescue or behavioural avoidance.

Larval transport and survival: Extended pelagic phase (~1 year) creates absolute dependency on: (1) suitable water column conditions for survival, (2) encountering prey fields at correct developmental stages, (3) avoiding predators, (4) currents transporting larvae to appropriate settlement habitat. Hypothesis that alfonsino populations depend on large oceanic eddy systems (Alekseev et al. 1986) implies population viability requires stable circulation patterns maintaining connectivity between reproductive and juvenile zones.

Spawning timing: Regional variation (September-March Azores, March-June Madeira, July-September Canary Islands, July-August New Zealand) demonstrates environmental cueing, though specific triggers (temperature? photoperiod?) incompletely understood. Serial spawning over extended seasons requires consistently suitable conditions throughout reproductive period. Climate-driven shifts in thermal regimes could cause match-mismatch between larval emergence and optimal prey availability or transport conditions.

Climate change vulnerability: Warming could affect: developmental rates (faster hatching but potentially exceeding thermal tolerances), fertilization success (altered current patterns disrupting gamete encounter), larval survival (stratification changes affecting prey availability, oxygen levels), dispersal pathways (shifted circulation patterns altering connectivity), spawning timing (phenological shifts creating mismatches with prey or transport windows). Marine heatwaves could cause episodic mass mortality of eggs/larvae. Indian Ocean already experiencing rapid warming (Dalpadado et al. 2023),

enhanced stratification reducing productivity – direct impacts on alfonsino reproduction unknown but broadcast spawning provides no buffering mechanisms.

Synthesis and Rating Justification:

HIGH dependency rating reflects confirmed broadcast spawning strategy with pelagic eggs, external fertilization, extended larval phase (~1 year), and complete absence of parental care across all studied populations. This reproductive mode creates multiple critical environmental dependencies throughout early life history.

Warming could affect: developmental rates (faster hatching but potentially exceeding thermal tolerances), fertilization success (altered current patterns disrupting gamete encounter), larval survival (stratification changes affecting prey availability, oxygen levels), dispersal pathways (shifted circulation patterns altering connectivity), spawning timing (phenological shifts creating mismatches with prey or transport windows). Marine heatwaves could cause episodic mass mortality of eggs/larvae. Indian Ocean already experiencing rapid warming (IO Climate Summary), enhanced stratification reducing productivity -- direct impacts on alfonsino reproduction unknown but broadcast spawning provides no buffering mechanisms.

Not MODERATE because: Broadcast spawning represents one of the most environmentally dependent strategies in marine fishes. Complete absence of: parental care, nest sites, ability to relocate offspring, capacity to delay hatching until conditions improve. Multiple life stages (fertilization, egg development, larval survival, transport, settlement) all critically dependent on oceanographic conditions with no compensatory mechanisms. This dependency level is definitionally HIGH.

Not LOW/MODERATE because: Even species with some parental care or substrate-associated eggs (MODERATE dependency) have mechanisms to buffer offspring from environmental variability. Alfonsino have none. Broadcasting millions of gametes into open water and hoping conditions align for 1+ year of pelagic development creates maximum environmental dependency.

S7;A4: Spawning Cycle Sensitivity to Seasonal and Temperature Cues

What Information IS Available:

Serial Spawning Strategy with Multi-Month Periods: Alfonsino are confirmed serial spawners across all studied populations, spawning repeatedly over extended periods rather than in single synchronous events. This reproductive strategy inherently provides temporal risk-spreading---if environmental conditions are unsuitable during early spawning events, later spawning opportunities exist within the same season. Multiple developmental stages collected simultaneously (Kuboshima 1995) demonstrates continuous or repeated spawning throughout the reproductive season rather than concentrated pulses.

Regional Spawning Timing Patterns: Multi-basin data document clear regional variation in spawning periods, demonstrating environmental cueing of reproductive timing:

- Macaronesian archipelagos (Atlantic): September-March (Azores), March-June (Madeira), July-September (Canary Islands)---clear north-south latitudinal gradient spanning 8 months
- New Zealand (Pacific): July-August spawning period
- Izu Islands, Japan (Pacific): Early morning concentration (02:00-06:00) suggesting diel optimization

The 8-month variation across Macaronesian populations separated by only 10 degrees latitude (Azores \~38°N to Canary Islands \~28°N) demonstrates strong environmental coupling of spawning timing to regional conditions. This latitudinal pattern suggests either temperature gradients or photoperiod variation (or interaction of both) drive regional timing differences.

Diel Timing Pattern: Concentrated spawning during early morning hours (02:00-06:00) at Izu Islands indicates behavioural timing potentially optimized for favorable oceanographic conditions (e.g., reduced turbulence, optimal current patterns for egg retention, reduced predation on gametes). This fine-scale temporal patterning demonstrates alfonsino respond to environmental cues at multiple scales---seasonal (months), lunar (potentially), and diel (hours).

Temperature Sensitivity of Biological Processes: Lehodey & Grandperrin (1996) established that alfonsino growth rates respond to temperature variability with 7.5-month lag to ENSO cycles. El Niño events (warmer temperatures) increased growth rates; La Niña events (cooler) reduced them. This demonstrates alfonsino physiology is temperature-sensitive and responds to oceanographic variability. While this addresses somatic growth rather than reproduction directly, temperature-sensitive growth strongly suggests reproductive processes are similarly influenced by thermal conditions.

What Information IS NOT Available:

SIOFA-Specific Spawning Timing: No published data document when alfonsino spawn in SIOFA Agreement Area. Critical unknowns include whether spawning is seasonal or year-round, which months, spawning duration, and whether timing varies across SIOFA seamounts/subareas. However, the multi-basin consistency of serial spawning strategy (3-6 month periods) provides reasonable expectation that SIOFA populations follow similar extended spawning patterns.

Cue Mechanisms Controlling Spawning Initiation: Which environmental cues trigger spawning onset and cessation? Key unknowns include temperature thresholds, photoperiod cues, interaction effects between temperature and photoperiod, productivity/prey cues, and oceanographic cues. The latitudinal gradient in Macaronesian spawning provides circumstantial evidence that temperature and/or photoperiod drive timing, but specific mechanisms remain unidentified.

Synthesis and Rating Justification:

AMBER rating reflects substantial proxy evidence from multiple ocean basins demonstrating serial spawning with regional timing variation, combined with critical knowledge gaps about SIOFA-specific patterns and cue mechanisms.

Evidence supporting moderate sensitivity assessment: Serial spawning provides temporal risk-spreading through multi-month spawning periods (3-6 months documented), inherently buffering against short-term environmental variability. Regional variation demonstrates adaptability---the 8-month range across Macaronesian populations shows alfonsino can adapt timing to regional environmental regimes. Environmental cueing is confirmed but mechanisms unknown, creating uncertainty about whether photoperiod-cued timing persists despite warming or temperature-cued timing shifts tracking climate change.

Not RED because: Substantial multi-basin data demonstrate serial spawning patterns, regional timing variation indicating environmental adaptability, and temperature-sensitive biological processes. Serial spawning over extended periods provides inherent buffering that synchronous spawners lack.

Not GREEN because: Critical gaps remain regarding SIOFA-specific spawning timing, cue mechanisms controlling phenology, temperature thresholds, and match-mismatch vulnerabilities. Cannot quantify specific sensitivities without understanding whether timing is primarily temperature-cued (high climate sensitivity) or photoperiod-cued (lower sensitivity but match-mismatch risks).

CRITICAL PRIORITY research for SIOFA populations: Investigate spawning seasonality/regional variation in spawning patterns and identify environmental cues.

S8;A4: Age at Maturity

What Information IS Available:

Sexual maturity varies regionally: 4-6 years at 30-34 cm (González et al. 2003), 6-8 years in New Caledonia (Lehodey et al. 1997), and 7-8 years at 40 cm in Chilean waters (Roa-Ureta 2008, Guerrero & Arana 2009).

This late maturity is a K-selected life history trait associated with high vulnerability to fishing and low population productivity. Catch data available: SIOFA (2025, SC-10-14-Rev1) reported annual catches averaging 3,698 tonnes across Subareas 2-4. Catches have been relatively stable in recent years, though historical catch levels from early fishing periods are not comprehensively documented. The fishery targets seamount aggregations using bottom trawls and midwater trawls. Age validation uncertainty: The SIOFA Age Validation Study (2023) applied radiocarbon dating to the congener Beryx decadactylus and revealed longevity of 50-70 years---3 to 5 times higher than previous estimates of 10-25 years based on whole otolith ageing. This discovery indicates the Berycidae family has been systematically underaged. While the study focused on B. decadactylus, the close taxonomic relationship and similar ecology strongly suggest B. splendens shares extended longevity, though direct validation for B. splendens in Indian Ocean remains incomplete.

What Information IS NOT Available:

Indian Ocean-specific maturity data: While Pacific populations show maturity at 6-8 years, Indian Ocean populations have not been directly studied. Regional variation in growth rates could affect maturity age. Faster-growing populations might mature earlier; slower-growing populations later. Environmental differences between Pacific and Indian Ocean (temperature, prey availability, fishing pressure) could influence maturation schedules.

Size at maturity unknown: Studies report age at maturity (6-8 years) but corresponding length and weight at maturity are not well-documented for SIOFA populations. Size at maturity is critical for fishery management (minimum size limits) and for assessing whether fishing selectively removes mature individuals before they reproduce.

Population health status poorly characterized: SIOFA (2025) provides catch data but comprehensive stock assessment has not been completed. Critical unknowns:

- Current biomass relative to unfished levels (depletion status) • Fishing mortality rate relative to sustainable levels
- Population trends (increasing? stable? declining?)

- Age/size structure (truncated by fishing or relatively intact?)
- Recruitment patterns (consistent? variable? declining?) Without stock assessment, cannot confidently characterise population health.

Historical baseline unknown: Pre-fishing abundance and distribution are not documented, making it impossible to assess cumulative fishing impacts. Have populations been depleted from virgin biomass? Are current distributions contracted from historical ranges? Unknown baseline prevents determining current population health status.

Recruitment monitoring: Are young cohorts successfully recruiting into the population? No systematic surveys monitor juvenile abundance or recruitment variability. Declining recruitment could indicate population health problems (overfishing, environmental degradation) but would go undetected without monitoring.

Genetic diversity: Middleton et al. (2023) initiated genetic stock structure. Genetic diversity is an indicator of population health---reduced diversity signals population bottlenecks potentially from overfishing or environmental stress. Effective population size (Ne) estimates would help assess whether populations are demographically healthy or declining.

Climate change impacts on population health: How have warming, productivity declines, or other climate drivers affected population productivity or health? The demonstrated temperature-growth relationship (Lehodey & Grandperrin 1996) and declining productivity in warm years suggest climate may already be affecting population dynamics, but monitoring to detect these signals is absent.

Maturity under climate change: Could warming affect maturation schedules? Some fish species show earlier maturity at smaller sizes under warming (temperature-size rule). Alternatively, if warming reduces growth rates through food web effects, maturity could be delayed. Maturation plasticity in response to environmental change is unstudied.

Synthesis and Rating Justification:

AMBER rating reflects well-documented maturity age from Pacific proxy but incomplete assessment of Indian Ocean population health. Framework questions can be partially answered:

Age at maturity: Well-established at 6-8 years (Lehodey et al. 1997, Guerrero & Arana 2009), confirmed across multiple Pacific locations. Late maturity is a K-selected trait with important climate vulnerability implications:

- Long pre-reproductive period: Individuals must survive 6-8 years before contributing to reproduction, creating extended vulnerability window
- Slow population recovery: If climate change or fishing reduces adult abundance, recovery requires 6-8 years minimum for new cohorts to mature
- Generation time: With potential longevity of 50-70 years (SIOFA 2023), generation time may be 30-40 years, meaning evolutionary adaptation extremely slow
- Fishing vulnerability: Late maturity combined with aggregative spawning behaviour makes populations highly vulnerable to overfishing

The 6-8 year maturity likely applies to Indian Ocean populations given consistency across Pacific regions and lack of evidence for substantial regional variation in Beryx life history patterns. However, direct validation would be valuable.

Population health status: Cannot be confidently assessed. Available information:

- Catches averaging 3,698 tonnes annually (SIOFA 2025) provide measure of exploitation level
- Fishery persistence suggests populations not collapsed, but sustainability unknown
- Catch stability in recent years could indicate: (a) healthy populations supporting consistent yields, (b) depleted populations with catch rates maintained through increased effort, or (c) management measures successfully stabilizing fishery.

Without stock assessment, population health determination requires cautious approach. Indicators suggesting potential concern:

- Late maturity (6-8 years) + extended longevity (50-70 years if validated) = very low productivity
- Seamount aggregations vulnerable to serial depletion (fishing moving between seamounts as populations decline)
- Lack of recruitment monitoring means population declines could be occurring undetected
- Climate pressures (warming, productivity declines) potentially reducing productivity even without overfishing

Comparison to other seamount species: Orange roughy populations globally showed severe depletion due to combination of late maturity (20-40 years), extreme longevity (100+ years), low productivity, and aggregative behaviour. If alfonsino share extended longevity (50-70 years), similar vulnerability exists. However, alfonsino mature earlier

than orange roughy (6-8 vs 20-40 years), providing somewhat higher productivity and faster potential recovery.

Not GREEN because: Indian Ocean maturity not directly validated. Population health status not quantitatively assessed. No stock assessment characterizing depletion, fishing mortality, or trends. Genetic diversity and recruitment patterns unknown.

Not RED because: Age at maturity well-established from multiple Pacific studies. Catch data available indicating fishery scale. Some monitoring in place through SIOFA reporting. Framework questions partially answerable with caveats.

HIGH PRIORITY research: Complete stock assessment including age structure, biomass estimates, and fishing mortality rates. Validate age at maturity for Indian Ocean populations directly. Implement recruitment monitoring. Complete genetic diversity assessment (as recommended in Middleton et al. 2023). Develop population model incorporating validated longevity estimates to assess sustainability. Monitor population trends and environmental drivers.

S9;A5: Prey Specificity and Dietary Flexibility

What Information IS Available:

Comprehensive Pacific diet composition: Kodama et al. (2025) provided the most detailed alfonsino dietary analysis to date, examining 708 stomachs from Pacific populations across Emperor Seamount Chain and Northwest Pacific Ridge. Diet composition comprised:

- Micronektonic fish: 48.6% (dominant prey category)
- Shrimp and decapod crustaceans: 24.3%
- Squid and cephalopods: 15.7%
- Other prey: 11.4% (including smaller contributions from various taxa)

This dietary breadth across three major prey groups (fish, crustaceans, cephalopods) indicates a generalist predatory strategy rather than specialist feeding. No single prey taxon dominates overwhelmingly, suggesting alfonsino feed opportunistically on available mesopelagic prey.

Mesopelagic prey community: Horn et al. (2010) documented alfonsino consumption of myctophids (lanternfish) and other mesopelagic species in New Zealand waters, consistent with the micronektonic fish category in Kodama et al. (2025). Myctophids are abundant mesopelagic fish that undergo diel vertical migration, making them accessible to alfonsino at seamount depths. The reliance on midwater prey rather than strictly

benthic organisms reflects the benthopelagic lifestyle.

Trophic level position: Alfonsino are secondary to tertiary consumers. This high trophic level indicates alfonsino feed on prey that are themselves predators (micronektonic fish eating zooplankton, squid eating small fish/crustaceans), creating multi-step connections between surface productivity and alfonsino nutrition.

What Information IS NOT Available:

No Indian Ocean dietary data: All comprehensive dietary studies come from Pacific populations (Kodama et al. 2025, Horn et al. 2010). Indian Ocean alfonsino diets have not been systematically studied. Regional differences in mesopelagic prey communities could result in different diet composition. While Pacific data provide reasonable proxy, Indian Ocean confirmation would strengthen confidence.

Dietary flexibility: While the generalist diet (three major prey groups with relatively balanced contributions) suggests potential flexibility, this hasn't been experimentally tested or observed under changing conditions:

- Can alfonsino shift diet composition if one prey group declines? For example, if micronektonic fish populations decrease, would alfonsino increase shrimp and squid consumption to compensate?
- Are there nutritional requirements that limit substitutability? Some predators require specific nutrients from particular prey types
- Do different prey groups provide equal energy content? If fish are more energy-rich than crustaceans, dietary shifts might not maintain nutrition
- What are limits to dietary flexibility? Could alfonsino survive if all three major prey groups declined simultaneously?

Prey availability and climate change: How will climate change affect alfonsino's prey community? Potential impacts include:

- Warming effects on mesopelagic fish, crustaceans, and cephalopods (differential sensitivities)
- Deoxygenation compressing vertical habitat for prey species
- Acidification impacts on crustacean shell integrity and cephalopod physiology
- Primary productivity declines cascading to mesopelagic prey abundance We lack data on prey species' climate vulnerabilities, making it impossible to predict whether dietary flexibility would be sufficient.

Seasonal and ontogenetic diet variation: Does diet composition change seasonally (following prey availability cycles)? Do juveniles eat different prey than adults? Understanding natural diet variation would help assess adaptive capacity. If alfonsino

already shift diet composition in response to seasonal prey fluctuations, this demonstrates flexibility that might enable climate adaptation. If diet is rigid year-round, flexibility may be limited.

Spatial diet variation: Kodama et al. (2025) studied two Pacific locations (Emperor Seamount Chain and Northwest Pacific Ridge). Do different seamounts support different prey communities requiring different alfonsino diets? Or is diet composition consistent across seamounts? Spatial variation in diet would indicate flexibility and ability to exploit different prey assemblages.

Foraging behaviour and prey selection: How do alfonsino locate and capture prey? Visual predation, chemosensory detection, opportunistic filter feeding? Understanding foraging mechanisms would help predict whether alternative prey could be effectively exploited if primary prey decline. Are prey selection patterns based on abundance (eating whatever is most available) or preference (targeting specific prey even when less common)?

Competition with other predators: Multiple mesopelagic predators (other fish species, squid, marine mammals) likely compete for similar prey. If climate change alters prey availability, would intensified competition limit alfonsino's ability to shift diet? Or could reduced competitor abundance (if competitors are more climate-sensitive) actually improve alfonsino prey access?

Synthesis and Rating Justification:

AMBER rating reflects good baseline diet data from Pacific proxy showing generalist strategy, but untested dietary flexibility and unknown prey vulnerability to climate change. Framework questions can be partially answered:

Likelihood of dietary change capacity: The generalist diet with three major prey groups (fish 48.6%, crustaceans 24.3%, cephalopods 15.7%; Kodama et al. 2025) suggests moderate likelihood of dietary flexibility. Evidence supporting flexibility:

- No single prey type dominates overwhelmingly---diet is taxonomically diverse
- Multiple prey groups indicate alfonsino can capture and consume varied prey types (different sizes, behaviours, defenses)
- Opportunistic feeding on abundant mesopelagic prey suggests foraging strategy is exploitation of available resources rather than specialization
- Generalist predators typically show greater dietary plasticity than specialists

However, important caveats:

- Dietary flexibility not empirically tested---we observe diverse diet under current conditions but don't know limits to flexibility
- If all major prey groups decline simultaneously (plausible under basin-wide productivity collapse; IO Climate Summary), dietary flexibility cannot compensate
- Prey groups may not be nutritionally equivalent---shifts could cause energy deficits affecting growth/reproduction
- Trophic level 4.0-4.5 position means alfonsino experience amplified effects of productivity changes through cascading food web impacts

Prey specificity: Low to moderate specificity. While diet shows some structure (fish > crustaceans > cephalopods), this likely reflects prey abundance in mesopelagic communities rather than strong preference. The diverse taxonomic composition within each major group (multiple fish families, various crustacean types, different cephalopod species) indicates broad acceptance of prey items. This is characteristic of generalist predators with relatively low prey specificity.

Comparison to other seamount species: Orange roughy show relatively specialist diets focused on mesopelagic fish and crustaceans with less dietary breadth than alfonsino. If alfonsino are more generalist, this suggests greater dietary flexibility and potentially lower climate vulnerability through food web pathway. However, both species occupy high trophic levels experiencing amplified productivity change impacts.

Climate change implications: Dietary flexibility provides some resilience buffer but significant uncertainties:

- Prey responses to climate change unknown: Are fish, crustacean, and cephalopod prey equally vulnerable? If differential, alfonsino might shift toward more resilient prey
- Basin-scale productivity declines (IO Climate Summary) affect all prey groups simultaneously
- Seamount productivity mechanisms may buffer against open ocean productivity declines (current-driven upwelling, retention), but this is unstudied
- Dietary shifts under stress may be possible but at energetic cost (reduced growth, delayed maturity, lower fecundity)

Indian Ocean dietary data essential: Pacific proxy provides foundation but regional differences in prey communities could mean different dietary flexibility. For example, if Indian Ocean seamounts support fewer cephalopod prey, crustacean and fish groups become more critical, reducing effective dietary flexibility.

Not GREEN because: Dietary flexibility not experimentally tested. Indian Ocean diet composition unknown. Prey climate vulnerability unstudied. Cannot confidently predict whether flexibility is sufficient under projected climate changes.

Not RED because: Comprehensive Pacific dietary data available. Generalist strategy evident. Moderate prey specificity suggests flexibility. Framework question partially answerable with caveats.

AMBER rating reflects good baseline diet data from Pacific proxy showing generalist strategy, but untested dietary flexibility and unknown prey vulnerability to climate change. Framework questions can be partially answered:

Likelihood of dietary change capacity: The generalist diet with three major prey groups (fish 48.6%, crustaceans 24.3%, cephalopods 15.7%; Kodama et al. 2025) suggests moderate likelihood of dietary flexibility. Evidence supporting flexibility:

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Indian Ocean dietary data essential: Pacific proxy provides foundation but regional differences in prey communities could mean different dietary flexibility. For example, if Indian Ocean seamounts support fewer cephalopod prey, crustacean and fish groups become more critical, reducing effective dietary flexibility.

S10;A10: Competition for Habitat and Resources

What Information IS Available:

Species co-occurrence documented: SIOFA (2025, SC-10-14-Rev1) reported alfonsino co-occurring with orange roughy (Hoplostethus atlanticus), oreos (Allocyttus spp., Pseudocyttus spp., Neocyttus spp.), and other seamount-associated species in catches from Subareas 2-4. This co-occurrence indicates spatial overlap in habitat use---multiple species aggregate on the same seamounts, creating potential for resource competition. For example, orange roughy and alfonsino both:

- Associate with seamount topography
- Occur at similar depth ranges (though orange roughy typically deeper: 600-1200m vs alfonsino 400-600m)
- Form aggregations over seamount features
- Support commercial fisheries targeting seamount aggregations Habitat overlap suggests potential competition for space, though depth segregation may reduce direct competition.

Overlapping prey consumption likely: Kodama et al. (2025) showed alfonsino consume micronektonic fish (48.6%), crustaceans (24.3%), and cephalopods (15.7%). Orange

roughy are known to consume similar mesopelagic prey (myctophids, crustaceans). Other seamount-associated species (oreos, cardinalfish) likely also exploit mesopelagic prey communities, creating potential dietary competition.

What Information IS NOT Available:

No competition studies exist: Competitive interactions between alfonsino and other seamount species have not been studied. We lack data on:

- Whether competition actually occurs (co-occurrence doesn't prove competition---resources may be sufficient for all species)
- Competition intensity (weak? strong?) • Which resources are competed for (prey? space? spawning habitat?)
- Which species are dominant vs subordinate competitors
- How competition affects growth, survival, reproduction, or distribution

Resource partitioning mechanisms unknown: Do co-occurring species reduce competition through niche partitioning? Possible mechanisms:

- Depth segregation: Orange roughy typically deeper (600-1200m) than alfonsino (400-600m), reducing spatial overlap
- Temporal partitioning: Different species feeding at different times (day vs night, different seasons)
- Dietary specialization: If co-occurring species focus on different prey types, competition minimized
- Habitat microhabitat use: Different species using summit vs flanks vs lee areas of seamounts

Evidence for or against these mechanisms is absent.

Competitive ability unassessed: In competitive interactions, some species outcompete others through:

- Superior foraging efficiency (capturing more prey per unit effort)
- Aggressive behavior (excluding competitors from resources)
- Physiological tolerance (functioning better under suboptimal conditions)
- Numerical dominance (more abundant species may monopolize resources)

Whether alfonsino are competitively dominant, subordinate, or intermediate is completely unknown.

Climate change effects on competition: How will warming, productivity declines, or habitat changes affect competitive dynamics?

- If prey declines, competition intensity likely increases as multiple species vie for limited food

- If suitable seamount habitat contracts (e.g., OMZ expansion compressing vertical habitat), spatial competition intensifies
- If some competitors are more climate-tolerant, they may gain competitive advantage
- If dominant competitors decline due to climate sensitivity, subordinate species (potentially including alfonsino) could benefit from competitive release None of these scenarios can be evaluated without baseline competition data.

Capacity to reduce competition through behavioral change: Can alfonsino adaptively respond to competition by:

- Shifting depth distribution to avoid competitors?
- Changing diet to exploit different prey than competitors? • Altering activity patterns (feeding times, foraging locations)?
- Moving to different seamounts with fewer competitors?

Behavioral plasticity in response to competition is unstudied.

Fishing effects on competitive dynamics: Have fisheries altered species abundances, thereby changing competitive balance? If fishing depletes orange roughy (major competitor), would this benefit alfonsino through competitive release? Or if alfonsino have been fished heavily, have competitors expanded? Historical fishery impacts on community structure are not characterized.

Predator-prey interactions: Besides resource competition, do seamount species interact as predators-prey? Do larger species prey on smaller species? Are juvenile alfonsino vulnerable to predation by adult competitors? These trophic interactions affect population dynamics but are unstudied.

Synthesis and Rating Justification:

RED rating reflects near-complete absence of information on competitive interactions. Framework questions cannot be adequately answered:

Ability to adapt to reduce competition: Unknown. This question presupposes we understand: (1) whether competition currently occurs, (2) its intensity and impacts, and (3) species behavioral repertoire for competitive responses. Without evidence that competition actually limits alfonsino, assessing adaptive capacity is impossible. Potential adaptation mechanisms (depth shifts, dietary changes, seamount relocation) have been discussed under other indicators (Mobility, Distribution, Prey Specificity) but specifically in competitive context remain unstudied.

Level of competition: Unknown. Co-occurrence with orange roughy, oreos, and other seamount species (SIOFA 2025) creates opportunity for competition, but occurrence doesn't prove competition intensity. Competition could be:

- Negligible: Resources (prey, habitat) abundant enough that all species coexist without significant competition
- Moderate: Some competition occurring but not limiting population sizes
- Intense: Strong competition significantly affecting growth, survival, or reproduction of one or more species
- Asymmetric: One species (e.g., orange roughy) strongly affected while another (e.g., alfonsino) relatively unaffected, or vice versa We cannot distinguish among these scenarios without experimental or observational studies quantifying resource use, overlap, and population-level consequences.

Climate change implications: Competition dynamics may be critical for climate vulnerability but are completely unstudied. Two contrasting scenarios:

- Scenario 1 - Intensified competition: Climate change reduces prey availability (IO Climate Summary: productivity declining) and compresses habitat (OMZ expansion, thermal habitat loss). Multiple species compete for declining resources. Competitively inferior species decline faster. If alfonsino are subordinate, climate vulnerability is amplified by competition.
- Scenario 2 - Competitive release: Climate change differentially affects species. If competitors (e.g., orange roughy) are more climate-sensitive and decline, alfonsino might benefit from reduced competition, accessing greater resource availability. If alfonsino are relatively climate-tolerant, they could expand within seamount communities as competitors decline.

Without knowing competitive relationships, we cannot predict whether competition amplifies or buffers climate vulnerability. This is a major knowledge gap affecting overall climate risk assessment.

Comparison to terrestrial systems: Terrestrial climate change studies show competition strongly modifies species responses---some species expected to decline under warming actually increase due to competitor declines (competitive release), while others decline faster than predicted due to range-expanding competitors (competitive exclusion). Marine seamount communities likely exhibit similar dynamics but are unstudied.

Not AMBER because: Information too sparse for even tentative assessment. Co-occurrence documented but competition not demonstrated. Resource overlap inferred but not quantified. Competitive ability unknown. Climate effects on competition completely unstudied. Cannot reasonably estimate competition level or adaptive capacity.

CRITICAL PRIORITY research: Community ecology studies characterizing multispecies interactions on SIOFA seamounts. Quantify dietary and spatial overlap among co-occurring species. Experimental studies testing competitive interactions. Ecosystem modeling incorporating multiple species and climate drivers. Long-term monitoring detecting community shifts potentially driven by competition and climate change. Comparative studies across seamounts with varying species assemblages and fishing histories.

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