Evidence for Ecosystem Productivity Decline in School Shark (*Galeorhinus galeus*): Implications for Stock Assessment Reference Points.

Abstract

Stock assessments for school shark (*Galeorhinus galeus*) have traditionally employed reference points based on historical unfished biomass (B_0) estimates derived from 1927 baseline conditions. However, accumulating evidence suggests fundamental changes in ecosystem productivity that may invalidate these historical baselines.

Multi-decadal datasets were analysed, including systematic nursery habitat surveys, commercial fishery data, population genetic analysis, and regional oceanographic records. Systematic surveys demonstrated 60-90% declines in nursery habitat productivity between 1947-1956 and 1991-1997 periods, with complete functional loss documented in formerly critical areas. Sea surface temperatures in southeastern Australia have experienced significant warming over the past 80 years (Hobday and Pecl, 2014). Sea surface temperatures have increased by up to ~2°C at locations such as Maria Island in Tasmania, coinciding with documented regime shifts in marine ecosystem productivity.

Close-Kin Mark-Recapture (CKMR) analysis revealed fundamental inconsistencies between historical catch levels and genetic data under single-stock assumptions. Density-dependent responses (increases in juvenile growth rates) provided biological evidence for population decline below habitat carrying capacity.

Convergent evidence from habitat degradation, climate-driven regime shifts, and population structure complexity indicates that current ecosystem conditions cannot support historical productivity levels. Reference points based on 1927 B_0 estimates are scientifically inappropriate and should be replaced with approaches reflecting demonstrated ecosystem carrying capacity constraints.

Keywords: *Galeorhinus galeus*, stock assessment, reference points, regime shift, nursery habitat, productivity decline, CKMR

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1. Introduction

Stock assessment reference points form the foundation of science-based fisheries management, providing quantitative targets and thresholds for sustainable harvest strategies (Hilborn and Walters, 1992). Traditional approaches assume that populations can recover to historical unfished biomass levels (B_0) in the absence of fishing mortality, with reference points typically expressed as percentages of estimated virgin biomass (Punt and Smith, 2001). This assumption underpins harvest control rules and recovery planning across most contemporary fisheries management frameworks, including the Commonwealth Fisheries Harvest Strategy Policy, which guides all Commonwealth fisheries in Australia (DAFF, 2018).

However, accumulating evidence suggests that rapid environmental change may invalidate historical baselines for some species, particularly those dependent on specific habitat requirements or operating in ecosystems experiencing climate-driven regime shifts (Brander, 2007; King et al., 2015; Free et al., 2019). Climate-driven changes in marine ecosystems have resulted in widespread range shifts, with marine species moving poleward at average rates of 72.0 ± 13.5 km per decade (Poloczanska et al., 2013). These changes necessitate ecosystem-based approaches to fisheries management that account for environmental variability and long-term ecosystem trends (Hare et al., 2016; Hollowed et al., 2013).

School shark represent a critical case study for evaluating reference point validity under changing environmental conditions. This temperate shark species supports important commercial fisheries across multiple jurisdictions within the Southern and Eastern Scalefish and Shark Fishery (SESSF), primarily through the Gillnet, Hook and Trap (GHAT) sector. Current stock status is not known but the last time they were accurately estimated they were only 12% of original biomass, with the population having crashed by ~90% from historical levels (Thomson and Punt, 2009; AFMA, 2023).

School sharks exhibit complex life histories with distinct ontogenetic habitat requirements. Adults migrate widely across southern Australian waters, mixing on offshore feeding and spawning grounds (Stevens and West, 1997). Reproductive success depends on access to specific inshore nursery areas—shallow, protected bays and inlets with seagrass beds that provide optimal environmental conditions. These nursery habitats supply essential prey resources and predator refuge for juveniles during their first 1-2 years of life.

The commercial exploitation of school shark in Australia began in the early 20th century and peaked during the 1960s. Since then, the population has suffered significant decline, with current catches stabilised at <10% of historical peaks despite two decades of stringent management measures (Walker, 1998; Punt et al., 2000). While these measures have successfully stabilised catches, they have not yet produced clear evidence of population recovery to target levels.

Recent developments in population assessment methodology, particularly CKMR approaches, have provided new insights while revealing inconsistencies with traditional stock assessment assumptions (Thomson et al., 2020; Bravington et al., 2016). CKMR methods utilise genetic markers to identify kinship relationships within samples, providing absolute abundance estimates that are independent of fishing behaviour and therefore particularly valuable for heavily exploited species.

This study evaluates scientific evidence for ecosystem productivity decline in the school shark population and assesses implications for stock assessment reference point validity. We test the hypothesis that current ecosystem conditions cannot support historical productivity levels, rendering traditional B_0-based reference points scientifically inappropriate for management application.

2. Methods

2.1 Study System and Species

School shark are a temperate shark species exhibiting viviparous reproduction, with females producing small litters (~28 pups) following 12-month gestation. Sexual maturity occurs at 8-10 years for males and 12-15 years for females, with maximum lifespans of 40-50 years (Walker, 2007). Reproductive success is critically dependent on access to specific shallow coastal nursery areas. This life history creates inherent vulnerability to overexploitation due to limited reproductive output and slow population growth rates (Stevens and West, 1997).

Commercial catch data were obtained from the Australian Fisheries Management Authority (AFMA) databases covering the GHAT sector of the SESSF from 1969 to 2024, including annual catch totals, effort measures, and spatial distribution information.

2.2 Nursery Habitat Productivity Assessment

Nursery habitat productivity was assessed using catch-per-unit-effort (CPUE) data from three distinct survey periods: 1947-1956 (Olsen, 1954), 1991-1997 (Stevens and West, 1997), and 2012-2014 (McAllister et al., 2018). Although survey methodologies varied between periods, all studies employed consistent gear types (longlines and gillnets) deployed at standardised locations within each nursery area to enable temporal comparisons. Age-0+ individuals (young-of-year) were used as the primary indicator of nursery habitat functionality, as recruitment success reflects recent reproductive output and habitat suitability (Beck et al., 2001).

2.3 Population Structure Analysis

Population structure was evaluated using two approaches: (1) multi-stock population modelling; and (2) CKMR genetic analysis. Multi-stock modelling tested single-stock versus two-stock (eastern/western) hypotheses, examining regional differences in catch decline patterns during the 1980s-1990s as described in Punt et al. (2000).

CKMR genetic analysis followed methods described in Thomson et al. (2020) and Bravington et al. (2016). Genetic samples were collected from commercial catches and research surveys, with kinship analysis identifying parent-offspring pairs (POPs) and half-sibling pairs (HSPs). Adult abundance estimates were derived from kinship encounter rates. Model validation tested whether genetic data could reconcile with historical catches exceeding 2,000 tonnes annually, including scenarios with optimistic biological parameters (100% annual female reproduction and 100% pup survival) to assess maximum plausible exploitation levels under single-stock assumptions.

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3. Results

3.1 Historical Catch Patterns

The school shark fishery peaked in 1969 at 2,543 tonnes, followed by sharp decline to ~700 tonnes by 1973 due to mercury content concerns. Catches rebounded to approximately 2,000 tonnes by 1986, representing nearly 80% of the historical peak. This resurgence may have indicated either a genuine population recovery or unsustainable exploitation of the remaining biomass. The sustained decline in catches through the late 1980s and 1990s, reaching ~500 tonnes by 2000, supports the latter interpretation.

Spatially disaggregated data revealed steeper declines in western regions (South Australia, western Victoria) during the late 1980s-1990s compared to eastern areas, despite uniform management measures, suggesting underlying biological or environmental differences (Punt et al., 2000). Catches have stabilised at ~200 tonnes, over the last two decades, representing <10% of the historical peak. This coincides with the introduction of stringent management measures under the School Shark Rebuilding Strategy, first implemented in 2009 (AFMA 2015).

3.2 Nursery Habitat Productivity Decline

Comprehensive surveys by Olsen between 1947 and 1956 established baseline conditions for school shark nursery areas across southern Australia. In Tasmania, areas such as Port Sorrell, Georges Bay, Upper Pittwater, and the D'Entrecasteaux Channel supported dense age-0+ populations with consistent annual recruitment. Nursery areas in Victoria such as Western Port, Port Phillip Bay (western side), and Swan Bay were similarly highly productive.

Follow-up surveys by Stevens and West (1991-97) revealed dramatic declines relative to these historical baselines. CPUE dropped by 60-90% across most previously productive nursery areas, with pups entirely absent in Georges Bay and the D'Entrecasteaux Channel. Widespread habitat degradation, particularly in Victorian waters, contributed to these declines. Western Port Bay lost 17,800 hectares of seagrass habitat between the 1970s and 1980s, representing an 85% decline from 25,000 to 7,200 hectares (Tanner et al., 2014). This loss has been recognized internationally as an ecological disaster (Waycott et al., 2009). Port Phillip Bay experienced variable seagrass changes, with some areas showing severe losses of up to 91% between 1998 and 2006, particularly in channels affected by altered freshwater flows and industrial pollution (Ball et al. 2014).

Biological responses included accelerated growth in juveniles (above historical levels) and shifts in age structure toward older juveniles, suggesting reduced recruitment and density-dependent effects. Adult growth rates remained unchanged, indicating effects were confined to nursery habitats rather than adult feeding grounds (Stevens and West, 1997).

McAllister et al. (2018) reported stable or slightly increased young-of-year abundance in Upper Pittwater and nearby Frederick Henry Bay. While these two nursery areas show limited signs of recovery, the documented loss of multiple historically productive nursery sites has reduced the overall nursery habitat capacity, constraining population recovery potential (McAllister et al., 2018; Stevens and West, 1997).

3.3 Population Structure Evidence

Single-stock assessment models could not satisfactorily account for the regional differences in catch decline patterns during the 1980s-1990s (Punt et al., 2000). While a two-stock approach with separate eastern and western components improved the model performance, Punt et al. (2000) noted that the true population structure probably involved additional complexity beyond this basic east-west division.

This complexity was further confirmed by CKMR analysis (Thomson et al., 2020), which revealed fundamental inconsistencies between historical catch levels and contemporary genetic data. Even when assuming extremely optimistic biological parameters—including 100% annual female reproduction and 100% pup survival—single-stock models could not reconcile observed kinship patterns with the historical catches that regularly exceeded 2,000 tonnes annually.

The CKMR-derived abundance estimates were substantially lower than what would be required to sustain such historical exploitation levels. This discrepancy provides quantitative evidence for either severe population depletion or a complex population structure involving multiple semi-independent breeding populations that collectively supported the historical fishery.

3.4 Climate-Driven Ecosystem Change

Sea surface temperatures in southeastern Australia have undergone significant warming over the past 80 years (Hobday and Pecl, 2014). Independent monitoring data shows temperature increases up to ~2°C at locations such as Maria Island in Tasmania, with this warming affecting coastal regions that include key school shark nursery areas and coincides with broader declines in marine ecosystem productivity.

The impacts of such environmental changes on fisheries productivity are already recognised in Australian fisheries management. The eastern stock of jackass morwong (*Nemadactylus macropterus*) provides a relevant precedent, having experienced persistent recruitment failure despite reduced fishing pressure. In response, AFMA formally recognised a shift in the productivity regime and revised management reference points and updated estimates of unfished recruitment (R_0) to reflect lower productivity under current environmental conditions (AFMA, 2019).

While species-specific thermal tolerance studies for school shark are limited, research on related shark species provides strong indication of likely physiological impacts. Studies on tropical sharks such as epaulette sharks (*Hemiscyllium ocellatum*) demonstrate that elevated temperatures significantly reduce embryonic survival rates, with survival dropping from 82% under current conditions to only 11% under high warming scenarios (Wheeler et al., 2024)

Warming patterns exhibit pronounced spatial heterogeneity across the southeastern Australian region, creating a complex mosaic of thermal conditions across different nursery areas. Some locations have experienced temperature increases exceeding 2.5°C, while others show more modest warming of 1-1.5°C. This spatial variability in thermal stress may explain the observed differential patterns in recruitment success and population recovery potential among geographically separated nursery areas, with more severely warmed locations showing greater declines in juvenile abundance.

Temperature increases compound other environmental changes affecting school shark nursery habitat suitability. Altered precipitation patterns and coastal development have modified freshwater discharge regimes, leading to elevated salinity levels in critical nursery areas including Port Phillip Bay and Western Port. School shark pups demonstrate sensitivity to salinity levels above species-optimal ranges, with elevated salinity reducing habitat suitability during early development phases. The combination of thermal stress and salinity changes creates synergistic impacts that exceed the effects of either stressor alone.

The implications of these environmental changes are particularly severe for school sharks due to their limited adaptive capacity. Strong natal site fidelity means individuals return to specific nursery areas for reproduction, preventing rapid geographic adaptation to changing conditions.

Combined with extremely slow reproductive rates (12-15 year maturation period, 12-month gestation, small litter sizes), these life history constraints severely limit the species' ability to adapt to rapidly changing environmental conditions. Consequently, environmental degradation of specific nursery areas creates long-term bottlenecks that constrain population recovery potential regardless of fishing pressure reductions.

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4. Discussion

4.1 Convergent Evidence for Productivity Decline

Multiple independent lines of evidence support fundamental decline in school shark productivity. Nursery habitat surveys provide the strongest evidence for irreversible productivity decline, including complete functional loss in productive sites like Georges Bay and D'Entrecasteaux Channel.

Western Port's loss of 17,800 hectares of seagrass habitat represents permanent reduction in ecosystem carrying capacity that cannot be reversed through fishing pressure reduction alone. Seagrass ecosystems require 10-50 years for recovery even under optimal conditions (Orth et al., 2006), and many areas have transitioned to alternative stable states dominated by algal mats and bare sediment. These changes represent a permanent reduction in ecosystem carrying capacity.

CKMR analysis provides quantitative validation that current ecosystem conditions cannot support historical exploitation levels. The statistical impossibility of reconciling genetic data with historical catches under single-stock assumptions constitutes the strongest evidence for fundamental productivity decline.

Documented regime shifts in related species (jackass morwong) and AFMA's precedent for reference point revision provide institutional framework for acknowledging productivity decline.

4.2 Mechanisms of Irreversible Decline

Habitat degradation in key nursery areas appears irreversible due to three key mechanisms:

1. **Seagrass Ecosystem Collapse**: Seagrass beds provide essential ecosystem services, including prey availability, predator protection and thermal buffering. Loss of seagrass beds eliminates these services, increasing juvenile mortality and thermal stress. Once degraded, seagrass bed recovery is extremely slow due to altered sediment dynamics, changed light availability, extreme weather events, and loss of seed banks (van Katwijk et al., 2016). Alternative stable states such as

algal mats and bare sediment resist restoration efforts, with successful restoration occurring in only 37% of attempts globally (Bayraktarov et al., 2016).

2. **Hydrological Modifications**: Coastal development permanently altered estuarine conditions through changed freshwater inflow, salinity regimes, and nutrient loading. These modifications make habitats unsuitable for school shark pups even if seagrass coverage recovers.
3. **Connectivity Loss**: Coastal infrastructure disrupts physical connections between nursery and adult habitats, impeding recruitment even where habitat quality improves. Port developments, marina construction, and dredging activities have fragmented continuous seagrass meadows into isolated patches below minimum viable habitat size.
4. **Climate Change Acceleration:** Climate change exacerbates existing stressors and reduces nursery habitat recovery likelihood. Projections of 1-3°C additional warming by 2050-2100 may exceed physiological tolerance limits for juvenile school shark during critical developmental stages. Synergistic effects with ocean acidification and declining dissolved oxygen suggest some systems have crossed ecological thresholds beyond which recovery of nursery habitats is no longer feasible.

Stevens and West (1997) concluded that remaining nursery areas are insufficient to sustain historical population levels, as spatial distribution of nursery areas is as important as total area for demographic resilience.

4.3 Implications for Reference Point Validity

Current reference points rely on assumptions that populations can recover to historical unfished biomass levels, presuming unchanged environmental carrying capacity. This assumption is contradicted by extensive evidence of irreversible habitat degradation and climate-driven productivity shifts. Recovery targets based on 1927 B_0 levels are no longer scientifically defensible, given current ecosystem capacity constraints.

CKMR-based assessments provide absolute abundance estimates that are incompatible with traditional reference points defined as percentages of B_0. This necessitates development of new decision criteria tailored to CKMR outputs and current productivity conditions.

AFMA's jackass morwong reference point revision demonstrates institutional capacity for acknowledging regime shifts and updating management frameworks. This precedent provides pathway for similar adaptations in school shark management.

4.5 Alternative Framework Requirements

Recognition of long-term productivity decline requires fundamental revision of management frameworks for school shark. Key components should include:

1. **Multi-Stock Assessment:** Population structure complexity necessitates multi-stock approaches acknowledging semi-independent breeding aggregations and differential productivity trends across regions.
2. **Climate-Adjusted Productivity:** Reference points should incorporate environmental constraints on recruitment success.

3. **Habitat-Based Targets:** Management objectives should ensure the protection and restoration of remaining functional nursery areas.
4. **Adaptive Management:** Regular review and adjustment of reference points based on updated environmental baselines, incorporating comprehensive monitoring of habitat quality, climate variables, and recruitment dynamics to ensure management responses align with changing environmental conditions.

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5. Conclusions

Multiple lines of convergent evidence demonstrate fundamental decline in school shark productivity, invalidating historical unfished biomass reference points. Current conditions cannot support historical productivity levels, making recovery to traditional benchmarks scientifically implausible regardless of fishing pressure.

Key Findings:

1. Nursery habitat productivity declined by 60-90% declines since 1950s baselines, with 17,800 hectares of critical seagrass habitat permanently lost
2. CKMR analysis provides definitive evidence that current population structure cannot support historical catch levels
3. Climate-driven warming is likely to exceed species tolerance thresholds in many historical nursery areas
4. Institutional precedent exists for reference point revision through AFMA's jackass morwong management adaptation.

The school shark case provides strong justification for adopting alternative reference point frameworks that acknowledge environmental change and carrying capacity constraints, with precedent existing through AFMA's jackass morwong regime shift responses.

School shark exemplify challenges facing long-lived marine species in rapidly changing environments, requiring management paradigms that evolve beyond historical baselines to remain effective and ecologically relevant. This case study provides a template for evaluating reference point validity for other climate-impacted species and demonstrates the need for adaptive management frameworks incorporating ecosystem change.

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