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REVIEW ARTICLE

Bridging single-species models to ecosystem-based maximum sustainable yield for environmental sustainability in marine fisheries

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ABSTRACT

Maximum sustainable yield remains a central biological reference concept in fisheries management. Its reliability is shaped by model assumptions, uncertainty, ecological interactions, and environmental change. The study objectives were to reconstruct the mathematical progression of maximum sustainable yield, from single-species deterministic models to ecosystem-based, multispecies formulations. The critical narrative review synthesizes the paradigm shift in ecological modeling, tracing its trajectory from equilibrium-based single-species frameworks to holistic, ecosystem-aware formulations. Classical production models are compared with age-structured, stock-recruitment, bioeconomic, precautionary, and multispecies approaches. The assumptions, data needs, uncertainty, and management implications are evaluated. Eight fisheries cases are used to illustrate contrasts in data availability, assessment methods, harvest rules, ecosystem awareness, and shared-stock governance. These cases are treated as illustrative examples rather than a representative validation sample. Evidence shows that trophic interactions can alter species-specific and system-level reference points. The direction of change depends on food-web structure, selectivity, interaction strength, environmental productivity, and management objectives. Environmental variation can also affect growth, recruitment, natural mortality, habitat capacity, and species interactions. Accordingly, biological reference points require adaptive updating when stock productivity exhibits nonstationarity, precluding their interpretation as rigid constants amidst shifting environmental conditions. Economic objectives, social needs, and conservation goals must also be distinguished from biological yield objectives. A five-dimension readiness framework is proposed as a preliminary hypothesis-generating heuristic. Alternative weighting schemes indicate that some borderline classifications are sensitive to assumptions. Independent validation and inter-rater testing are therefore required before operational use. While substantial data constraints persist across multiple Indonesian fisheries, these limitations must not be regarded as the sole impediment to comprehensive management. Governance, enforcement, fleet structure, socioeconomic incentives, habitat condition, and climate variability can independently affect performance. Greater use of adaptive monitoring, precautionary harvest rules, uncertainty analysis, and ecosystem indicators is therefore recommended. Multispecies assessment should be prioritized where trophic or technical interactions materially influence stock dynamics. Maximum sustainable yield is best retained as an analytical reference point rather than a literal catch target. Environmentally sustainable application requires precautionary, adaptive, and ecosystem-based governance frameworks dynamically aligned with local empirical data quality, ecological conditions, and institutional capabilities.

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INTRODUCTION

Fisheries management is essential to sustain fish resources as overexploitation, climate change, and habitat loss intensify. The Food and Agriculture Organization (FAO) estimates that 37.7 percent (%) of global marine fish stocks are overexploited and 50.5% are fished at maximum sustainable levels (FAO, 2024). Global fisheries production potential has contracted by roughly 4% since 1930 as a consequence of ocean warming (Free *et al*., 2019), compounded by illegal, unreported, and unregulated (IUU) fishing, which extracts an estimated 11-26 million tons annually outside formal management accounting (Agnew *et al*., 2009). Industrial fishing effort is concentrated among a small number of distant-water fleets (Kroodsma *et al*., 2018; McCauley *et al*., 2018), supported by about United States Dollar (US$)22 billion a year in capacity-enhancing subsidies (Sumaila *et al*., 2019). In Indonesia, enforcement against foreign IUU fishing after 2014 reduced fishing effort without reducing domestic catch (Cabral *et al*., 2018). Sustainable development goal (SDG) 14.4, calls for ending overfishing and restoring stocks to maximum sustainable yield (MSY) levels. National fisheries policy in Indonesia dictates that the annual total allowable catch (TAC) is established at 80% of the aggregate maximum sustainable yield (MSY) (Bappenas, 2020). Accordingly, Ministerial Decree No. 19 of 2022 sets a TAC of 8.6 million tons against an estimated national fish resource potential of 12.01 million tons annually (MMAF, 2022). However, independent assessment has found many Indonesian stocks overfished (Muawanah *et al*., 2018). The Ministry of Marine Affairs and Fisheries has also paired the quota system with a broader blue-economy program, although inter-agency coordination and funding remain challenges (Trenggono *et al*., 2025). The 80% provision is therefore treated as a policy buffer, not as evidence of ecological sustainability, because Its effectiveness depends on assessment quality, reporting, compliance, enforcement, ecosystem condition, and adaptive harvest control. While the theoretical origins of MSY precede Schaefer, Schaefer (1954) formulated its most influential mathematical framework, defining the upper bound of long-term sustainable yield under specific model constraints—a metric that subsequently became a cornerstone policy reference in the 1982 United Nations Convention on the Law of the Sea (UNCLOS), the 1995 United Nations Fish Stocks Agreement, the FAO Code of Conduct for Responsible Fisheries (FAO, 1995), and European fisheries policy (European Union, 2013). Mace (2001) described the shift from MSY as target toward a ceiling not to be exceeded. Nevertheless, Larkin (1977) challenged single-species MSY models, arguing that they inherently neglect ecological variability, multitrophic interactions, operational fishing costs, and socio-political distortion. Subsequent work developed age-structured, stock-recruitment, bioeconomic, precautionary, and ecosystem-aware, and management strategy evaluation (MSE) approaches (Punt *et al*., 2014). Global evidence indicates that actively managed fisheries can rebuild toward biomass levels compatible with sustainable harvest (Worm *et al*., 2009, Costello *et al*., 2016, Hilborn *et al*., 2020), suggesting that poor outcomes reflect misuse, overcapacity, uncertainty, and ecosystem effects rather than one mathematical concept alone (Beddington *et al*., 2007; Pauly and Froese, 2021). Recent studies continue to extend MSY-related modelling (Gillis *et al*., 2024; Chamera *et al*., 2025). This review therefore links model assumptions with environmental non stationarity, trophic interactions, uncertainty, management objectives, and implementation conditions. The current study pursues four primary objectives. First, the mathematical progression of MSY is critically reconstructed from deterministic single-species models to ecosystem-aware formulations. Second, conditions that weaken equilibrium reference points are identified. These conditions include environmental nonstationarity, trophic

coupling, and data uncertainty. Third, contrasting fisheries cases are compared without presuming the statistical equivalence of management units. Fourth, a preliminary readiness heuristic is proposed for organizing implementation evidence. Published literature and secondary sources available in 2026 were used. The study was conducted in the Department of Mathematics, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, Sumedang, Indonesia in 2026.

METHODOLOGY

Review design and methodological identity. The manuscript is a critical structured narrative review combining conceptual and mathematical synthesis with illustrative comparative case analysis. It is not a systematic review, meta-analysis, primary stock assessment, or validation study. Classical mathematical derivations are re-evaluated to compare foundational assumptions and contrast the outcomes yielded by alternative reference points. No new mathematical model is claimed. The readiness framework is an author-developed heuristic whose construction is separated from evidence describing individual fisheries. Search strategy and eligibility. Literature was searched in Scopus, ScienceDirect, Google Scholar, and direct institutional sources. Searches combined “maximum sustainable yield” or “MSY” with “surplus production”, “Schaefer”, “Pella-Tomlinson”, “Fox”, “Beverton-Holt”, “Ricker”, “bioeconomic”, “management strategy evaluation”, “multispecies”, “ecosystem-based”, “trophic”, “climate”, and “Indonesia”. Foundational studies published before 2015 were retained when they defined a model, reference point, or management concept. To maintain currency in empirical applications and current policy contexts, precedence was given to recent scholarly literature. Eligible sources addressed model assumptions, reference points, uncertainty, ecological interactions, or implementation. Sources were excluded when MSY served merely as an incidental parameter, the targeted management unit remained ambiguous, or foundational key claims lacked traceable scientific or official support. No prospective protocol complete deduplication log, or screening flow count was available. Evidence appraisal and synthesis. Peer-reviewed stock assessments, MSE studies, and ecosystem models were used for scientific inference. Official regulations and advice documents characterized operational rules. These reviews established the necessary historical and conceptual framework. Robust policy assertions were maintained exclusively when corroborated by multiple evidentiary forms, whereas model-dependent insights were articulated conditionally. Regarding case-study selection and comparability, eight distinct cases were chosen via maximum-variation purposive sampling, spanning data-rich versus data-limited, temperate versus tropical, single-stock versus multispecies, and domestic versus multilateral contexts. Each case was documented across data infrastructure, assessment methodology, harvest-rule enforceability, ecosystem awareness, and shared-stock governance. The heterogeneous cases illustrate contrasts rather than prevalence or causal effects. Framework construction and uncertainty. The five dimensions were scored on a three-level ordinal scale. Equal weighting was adopted as a transparent baseline configuration, with data-intensive, governance-intensive, and ecosystem-intensive alternatives evaluated via sensitivity testing. Weighted mean scores below 1.5 were classified as emerging, 1.5 to below 2.5 as transitional, and 2.5 or higher as advanced. Owing to the absence of an independent validation dataset and inter-rater testing, this framework should be interpreted as exploratory rather than a validated instrument (Table1).

Deterministic single-species models for MSY

All deterministic MSY derivations rest on a common mass balance identity. The rate of change of exploitable biomass equals biological

Table 1: Comparative synthesis of major MSY approaches

Approach	Core assumption/ objective	Ecological realism	Uncertainty treatment	Typical data need	Appropriate management use
Schaefer	Logistic surplus production; equilibrium MSY	Low; single stock, fixed productivity	Usually parameter/ process uncertainty only if extended	Catch-effort/CPUE time series	Transparent baseline when stock and environment are relatively stable
Pella-Tomlinson / Fox	Flexible production-curve shape	Low-moderate; still aggregate single stock	Sensitive to shape and parameter estimation	Catch-effort/CPUE with enough contrast to estimate shape	Alternative production forms; structural-uncertainty comparison
Beverton-Holt / Ricker + Y/R	Age/size processes and stock-recruitment feedback	Moderate; recruitment mechanism explicit but usually single stock	Can propagate recruitment and life-history uncertainty in modern assessments	Age/length composition, growth, mortality, maturity, recruitment	Stock-specific reference points when demographic data are available
Gordon-Schaefer/ MEY	Economic rent, prices, costs, fleet behavior	Biological realism similar to production model; economic dimension explicit	Economic and biological uncertainty can be simulated	Biological data plus prices, costs, effort behavior	Economic target setting; not a substitute for ecological limits
Precautionary HCR + MSE	Management procedure tested under observation, assessment, and implementation error	Potentially high if operating model includes ecosystem/climate processes	Explicit simulation of multiple uncertainty sources	Assessment data plus plausible operating-model scenarios	Testing robustness and trade-offs before implementation
Multispecies / ecosystem models	Species interactions and/or system-level objectives	High relative to single-species models, but model dependent	Parameter and structural uncertainty can be substantial and should be ensemble-tested	Diet/trophic, abundance, fleet/selectivity, environmental data depending on model	When trophic/technical interactions materially alter single-stock advice; results are context dependent

production minus removal by fisheries, $dB/dt = G(B) - C(B,E)$, where $B(t)$ is exploitable biomass at time t, $G(B)$ is a density dependent production function, and $C(B,E)$ is catch expressed as a function of biomass and fishing effort E. MSY is defined as the global maximum of the equilibrium yield curve $Y^*(E)$, obtained by setting $dB/dt = 0$ and solving for catch as a function of effort; MSY is then defined as the maximum of the resulting equilibrium yield curve.

The Schaefer logistic surplus production model

The simplest and most widely taught surplus production model treats production as a quadratic function of biomass, using Eq. 1 (Schaefer, 1954):

$$\frac{dB}{dt} = rB\left(1 - \frac{B}{K}\right) - qEB \quad (1)$$

Differentiating and setting the result to zero gives the classical Schaefer reference points, using Eq. 3 (Hilborn and Walters, 1992; Schaefer, 1954). Here, r is the intrinsic rate of population growth (per year), K is the carrying capacity (in biomass), q is catchability coefficient under fishing conditions, and E is fishing effort. Catch is defined as $C = q\,E\,B$ and instantaneous fishing mortality is $F = q\,E$. At equilibrium, given constant F, biomass is calculated as $B^* = K\,(1 - F/r)$, so equilibrium yield as a function of F, using Eq. 2 (Schaefer, 1954):

$$Y^*(F) = FK\left(1 - \frac{F}{r}\right) \quad (2)$$

Differentiating and setting the results to zero gives the classical Schaefer reference points, using Eq. 3 (Hilborn and Walters, 1992; Schaefer, 1954):

$$B_{MSY} = \frac{K}{2}, \quad F_{MSY} = \frac{r}{2q}, \quad MSY = \frac{rK}{4} \tag{3}$$

The Schaefer solution places maximum production at half of carrying capacity under the logistic assumption. While the Schaefer model dictates that fishing mortality at MSY equals half the intrinsic growth rate, this relationship constitutes an artifact of model architecture rather than a universal biological law. Furthermore, because real-world fish stocks frequently exhibit delayed responses to exploitation and asymmetric surplus production curves, the Schaefer formulation should function as a transparent analytical baseline rather than an unconditional default.

The pella-tomlinson generalized production model

Empirical yield curves for many stocks are skewed rather than symmetric, with maximum production occurring away from *K/2.* Pella and Tomlinson (1969) generalized the Schaefer model with a shape parameter *p*., using Eq. 4 (Pella and Tomlinson, 1969):

$$\frac{dB}{dt} = \left(\frac{r}{p}\right) B \left[1 - \left(\frac{B}{K}\right)^{p}\right] - qEB \tag{4}$$

The Pella-Tomlinson model generalizes the logistic production function by adding a shape parameter *p*. This parameter changes the biomass location of maximum production. Under the parameterization used here, *p = 1* recovers the Schaefer logistic model. Values below one give BMSY below *K/2*. Values above one give B_{MSY} above *K/2*. The terms "left-skewed" and "right-skewed" are avoided because their interpretation depends on the plotted variable. Reference points should instead be interpreted directly from B_{MSY}/K and F_{MSY}. The reference points are Eqs. 5 to 7 (Pella and Tomlinson, 1969):

$$\frac{B_{MSY}}{K} = \left(\frac{1}{p+1}\right)^{1/p} \Rightarrow B_{MSY} = K\left(\frac{1}{p+1}\right)^{1/p} \tag{5}$$

$$F_{MSY} = \frac{r}{P+1} \tag{6}$$

$$MSY = rK\left(\frac{1}{P+1}\right)^{\frac{p+1}{p}} \tag{7}$$

At *p = 1* this recovers the Schaefer result *MSY=rK/4* (Hilborn and Walters, 1992; Schaefer, 1954). As *p* approaches zero ($p \rightarrow 0$), both F_{MSY} approaches r and MSY approaches *rK/e* recovering the Fox (1970) exponential model as a special case. The implied F_{MSY} and B_{MSY} therefore depend on *p*. A shape-invariant Schaefer benchmark can bias reference points when the true production curve is asymmetric. The direction and magnitude of potential estimation bias should be rigorously assessed directly from the characteristics of fitted parameterization. A universal mapping between p and ecological guild is not assumed (Haddon, 2011; Polacheck *et al*., 1993). Other variations can also be found in Supriatna for different interpretations (Supriatna, 2012).

The fox and Gompert exponential model

A third model which replaces the logistic with a Gompertz growth function is expressed as Eq. 8 (Fox, 1970):

$$\frac{dB}{dt} = rB\ ln\left(\frac{K}{B}\right) - qEB \tag{8}$$

This produces a left-skewed yield curve with explicit reference points, using Eq. 9 (Fox, 1970):

$$F_{MSY} = r, \quad B_{MSY} = \frac{K}{e}, \quad MSY = \frac{rK}{e} \tag{9}$$

The Fox model's asymmetric curve yields higher MSY and F_{MSY} estimates than the Schaefer, making Schaefer the more conservative benchmark (Haddon, 2011), though Fox model has been widely applied to tropical tuna and small pelagic stocks (Fox, 1970). See also Supriatna and Husniah (2015) for further modification of this model.

Age-structured yield: Beverton-Holt yield-per-recruit

For long-lived demersal stocks, age at first capture matters as much as total effort. Under von Bertalanffy growth, exponential natural mortality, knife-edge selectivity, and a closed cohort, yield-per-recruit *(Y/R),* using Eq. 10 (Beverton and Holt, 1957):

$$\frac{Y}{R} = F\, e^{\{-M(t_c - t_r)\}}\, W_\infty \sum_{n=0..3} u_n\, e^{\{-\mathrm{n\,K}(t_c - t_0)\}} /(F + M + nK) \quad (10)$$

where $U_n = (-1)^n 3!/[n!\,(3-n)!]$. In Eq. 10, *M* denotes natural mortality and t_c denotes age at first capture. Age of recruitment is denoted by t_r. The von Bertalanffy parameters are t_0 and K. Asymptotic weight is denoted by W_∞. The remaining terms are standard summation coefficients. Maximizing yield per recruit over *F* provides Fmax. The more precautionary $F_{0.1}$ is defined where the yield-per-recruit slope falls to 10% of its value at the origin. $F_{0.1}$ is often used when stock-recruitment information is weak (Gulland and Boerema, 1973; Hilborn and Walters, 1992).

Stock-recruitment functions

Y/R analysis assumes constant recruitment per spawner, rarely defensible empirically. The Beverton-Holt function is asymptotic, using Eq. 11 (Beverton and Holt, 1957):

$$R = \alpha S/(1 + \beta S) \quad (11)$$

where *R* is recruitment, S is spawning biomass, α is the maximum per-capita recruitment, and β is a density-dependent saturation coefficient, giving a finite ceiling $R_\infty = \alpha/\beta$. The function is instead dome-shaped, using Eq. 12 (Ricker, 1954):

$$R = \alpha S e^{\{-\beta S\}} \quad (12)$$

Peaking at $S^* = 1/\beta$ before declining, consistent with density-dependent cannibalism or nursery habitat degradation. Both can be reparametrized in terms of the steepness $h = R(0.2S_0)/R_0$, the parameter of choice in modern integrated assessments such as Stock Synthesis (Methot and Wetzel, 2013). Combining yield-per-recruit with a stock-recruitment relationship, while maintaining self-consistency between the predicted recruitment and the spawning stock biomass, it generates yield F_{MSY}, using Eq. 13 (Beverton and Holt, 1957; Methot and Wetzel, 2013):

$$F_{MSY} = \arg\max_F \left[\frac{\alpha\emptyset(F) - 1}{\beta\emptyset(F)} . \frac{Y}{R}(F)\right] \quad (13)$$

where *ϕ(F)* is spawning biomass per recruit at fishing mortality *F.* The spawning potential ratio (SPR) function is expressed, using Eq. 14 (Clark, 1991):

$$SPR(F) = \frac{\emptyset(F)}{\emptyset_0} \quad (14)$$

Clark (1991) found $F_{35\%}$SPR approximates F_{MSY} across diverse groundfish, later revised to the more conservative $F_{40\%}$SPR (Mace, 1994) when the stock-recruitment relationship is unresolved. These diagnostics can also support data-limited assessment. Recent stock evaluations in Jakarta Bay reveal severe exploitation pressures alongside critically low spawning-potential ratios for key target species (Yuliana *et al.*, 2026). Fishing to natural mortality ratios also exceeded one under two length-based methods. This outcome illustrates the utility of demographic proxies in detecting stock overexploitation in data-limited environments where complete stock-recruitment relationships are absent.

Equilibria and local stability

The Schaefer model has three dynamical regimes depending on *F* relative to *r*. For *F < r,* equilibrium *B* = K (1 − F/r) > 0* is biologically meaningful and locally stable. At *F = r* the non-zero equilibrium collides with the origin in a trans

critical bifurcation, for $F > r$ only $B = 0$ is stable, and the stock declines to extinction. Even an analytically perfect Schaefer fishery is fragility around $F_{MSY} = r/2$, a doubling of effort, from fleet expansion or technical creep halving catchability, is enough to cross this bifurcation (Hilborn and Walters, 1992), underlying Mace's (2001) case for treating F_{MSY} as a limit rather than a target.

Yield curves and the asymmetry of production

The Schaefer equilibrium yield curve manifests as a symmetric inverted parabola, reflecting the mathematical constraints of the logistic production function rather than a universal biological property. Pella-Tomlinson and Fox formulations allow asymmetric production curves. Empirical life-history studies also show that B_{MSY}/K varies among stocks (Thorson *et al*., 2012; Zhou *et al*., 2012). Model choice can therefore alter FMSY and BMSY. Fig. 1. compares the mathematical forms without assigning a universal curve shape to any ecological guild.

Non stationarity and climate-sensitive reference points

Equilibrium MSY assumes sufficiently stable productivity and stock-environment relationships over the management horizon. This core assumption is compromised under conditions of temporal variability in recruitment, growth, natural mortality, habitat carrying capacity, or trophic structure. Given that thermal regimes and community dynamics systematically alter stock productivity and associated reference points (Free *et al*., 2019; Fulton *et al*., 2022), biomass and fishing mortality benchmarks must be operationalized as conditional parameters rather than immutable values. Periodic re-estimation, state-dependent reference points, or climate-conditioned operating models may therefore be appropriate under strong non stationarity. MSE is subsequently applied to test the resilience of candidate management procedures against a suite of plausible future conditions.

Identifiability problem of MSY parameters

Schaefer reference points depend on r and K. These parameters can be difficult to estimate from CPUE series. Their likelihood surface may contain a strong correlation ridge. MSY can sometimes be better determined than r or K separately (Hilborn and Walters, 1992; Punt, 2003). Responses include life-history based priors on r (Froese *et al*., 2016) and catch only and length-based methods such as catch-MSY (Martell and Froese, 2012) and length-based spawning potential ratio (Hordyk *et al*., 2015), though their assumptions require stock-by-stock basis (Free *et al*., 2020). Furthermore, structural uncertainty persists because alternative surplus production frameworks, including the Schaefer, Pella-Tomlinson, and Fox models can generate contrasting reference points when applied to the same stock.

Bioeconomic extensions: from MSY to MEY

The Gordon-Schaefer open-access model

Schaefer's biological model says nothing about the behavior. Gordon (1954) supplied the economic complement, with total revenue $TR(E) = p\,Y^*(E) = p\,q\,E\,K\,(1 - qE/r)$, where p is the unit price of catch, and total cost is $TC(E) = c\,E$, where c is the cost per unit of effort. Sustained economic rent, using Eq. 15 (Gordon, 1954):

$$\pi(E) = p\,q\,E\,K\left(1 - \frac{qE}{r}\right) - c\,E \qquad (15)$$

Setting $d\pi/dE = 0$ gives the effort maximizing sustainable rent, using Eq. 16 (Gordon, 1954):

$$E_{MEY} = \left(\frac{r}{2q}\right)\left(1 - \frac{c}{(pqK)}\right) \qquad (16)$$

In an open-access fishery, equilibrium effort is dictated by the complete dissipation of economic rent. When harvesting remains financially viable under conditions of low biomass, open-access effort frequently exceed levels corresponding to biological MSY, thereby driving fleet overcapacity

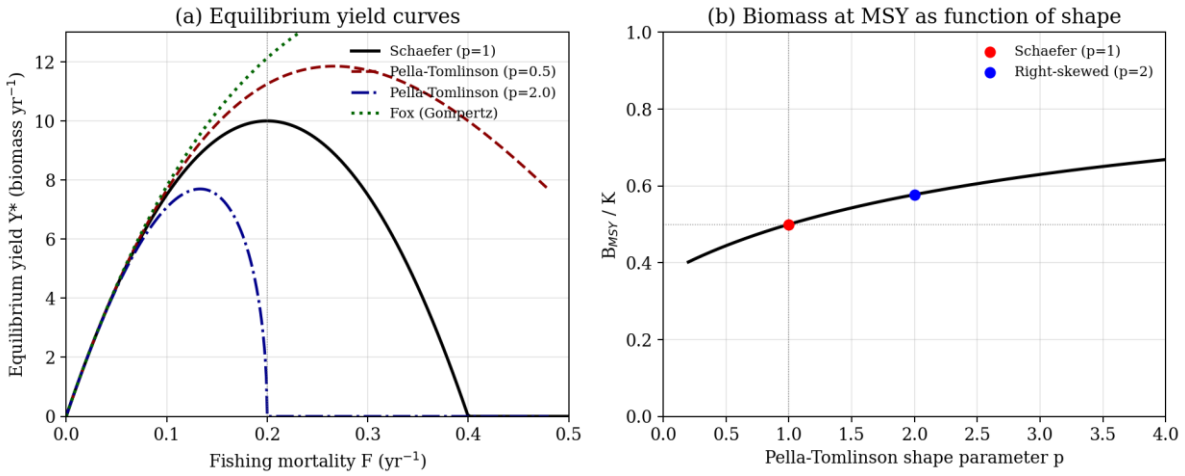

Fig 1: (a) Equilibrium yield curves for the Schaefer logistic (p = 1), two Pella-Tomlinson variations (p = 0.5 and p = 2), and the Fox-Gompertz model, calculated with r = 0.4 per year and K = 100. (b) Biomass at MSY as a fraction of carrying capacity as a function of the Pella-Tomlinson shape parameter p

and stock depletion. MSY, MEY, optimum yield (OY), and MSE each address distinct dimensions of fisheries governance: MEY serves as a biological production reference point; MEY integrates economic variables such as prices, operational costs, and fleet dynamics to establish an economic objective; OY accommodates broader social and ecological considerations; and MSE provides a simulation framework to test the robustness of alternative management procedures under uncertainty. Trade-offs among yield, profit, employment, food security, biodiversity, and catch stability require explicit performance criteria (Punt *et al*., 2014).

MEY as a management target

Several jurisdictions have formally adopted MEY. The Australian Commonwealth Fisheries Harvest Strategy Policy of 2007 (revised 2018) manage toward B_{MEY} as the target reference point, with half of B_{MSY} as the limit (Dichmont *et al*., 2010). Analyzing four distinct fisheries, Grafton *et al*. (2007) established that dynamic maximum economic yield corresponds to greater stock biomass and superior discounted economic returns relative to MSY. Global evidence also suggests that catch shares can reduce collapse risk (Costello *et al*., 2008). These benefits remain conditional on economic assumptions. Clark's (1973) showed that sufficiently high discount rates, the liquidation of a natural resource can constitute an economically rational strategy, even when secure property rights are established.

Optimal sustainable yield and multi-objective trade-offs

Both MSY and MEY remain single objective constructs, while real fisheries serve multiple legitimate objectives, employment, food security, biodiversity, and recreational. The United States 1976 Fishery Conservation and Management Act introduced the concept of OY as the catch providing the greatest overall national benefit, explicitly modifying MSY by economic, social, and ecological factors (National Research Council, 1998). In a parallel policy shift, the 2013 Common Fisheries Policy of the European Union integrates ecosystem and social considerations into its application of MSY (European Union, 2013). MSE fulfills a fundamentally different operational role, utilizing simulation testing to assess the performance of candidate management procedures across multiple performance metrics under uncertainty (Punt *et al*., 2014).

Precautionary and limit reference points

Mace (2001) reformulated F_{MSY} as a limit that fishing mortality should rarely or never exceed,

with a target set below it to buffer for assessment and implementation error. The International Council for the Exploration of the Sea (ICES) operationalizes this through paired target and limit reference points *(B_{pa}, F_{pa}) and (B_{lim}, F_{lim})* (ICES, 2021). Biological reference points define critical boundaries below which recruitment success is compromised, whereas target reference points are positioned with a sufficient margin of safety to maintain the probability of falling below B_{lim} stays around 5%. F_{MSY} in the ICES framework is now a precautionary target defined only in this buffered context (ICES, 2021; Mace, 2001), an architecture several reviews consider essential to any defensible operationalization of MSY (Punt *et al*., 2014).

Management strategy evaluation

MSE is a simulation framework for testing candidate management procedures under uncertainty (Punt *et al*., 2014; Smith, 1994). It links an operating model of "stock and ecosystem dynamics", an observation model, and a harvest control rule (HCR), then evaluated metrics such as mean yield, probability of being below B_{lim}, and catch variability across many simulated trajectories. MSE is now the standard procedure at the Commission for the Conservation of Southern Bluefin Tuna (CCSBT), the International Pacific Halibut Commission, the International Commission for the Conservation of Atlantic Tunas (ICCAT), and ICES. Its value lies in testing whether management procedures maintain resilience under real-world uncertainty, rather than presuming that a deterministic optimum will be operationally dependable (Punt, 2015; Punt *et al*., 2014).

Toward ecosystem-based MSY

Critique of single-species MSY

Larkin (1977) identified five shortcomings of single-species MSY, neglect of natural variability, spatial heterogeneity, species interactions, fishing costs, and political pressure. Later work developed responses to these limitations (Sissenwine, 1978; Mace, 2001; Walters *et al*., 2005). Among the evaluated dimensions, species interaction proved the most analytically tractable, owing to the availability of established discrete predator-prey formulations (Supriatna and Possingham, 1998, 1999). The following section focuses on continuous models. Institutional design can also address ecosystem concerns, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) established precautionary, ecosystem-based mandate from the outset, setting catch limits that account for the needs of dependent predator populations rather than single-species yield alone (Constable *et al*., 2000).

Predator-prey foundations of multispecies MSY

The classical Lotka-Volterra system represents prey density N and predator density *P* using coupled formulas, using Eq. 17 (Lotka, 1925):

$$\frac{dN}{dt} = rN - aNP, \qquad \frac{dP}{dt} = eaNP - mP \tag{17}$$

where *r* is intrinsic prey growth rate, *a* is the predator attack rate, *e* is the trophic transfer efficiency, and *m* is the predator natural mortality (Lotka, 1925). The non-trivial equilibrium *(N*, P*) = (m / (e a), r / a)* show equilibrium prey density set entirely by predator life-history parameters and equilibrium predator density set entirely by prey productivity and attack rate. The simultaneous integration of top-down predation pressure and bottom-up trophic limitation is formally expressed through coupled differential equations that underpin contemporary ecosystem-based fisheries theory (Andersen and Beyer, 2013; Walters *et al*., 2005). Introducing fishing mortality F_N and F_P on prey and predator, defined in Eq. 18 (May *et al*., 1979):

$$\frac{dN}{dt} = rN - aNP - F_N N, \qquad \frac{dP}{dt} = eaNP - mP - F_P P \tag{18}$$

Solving at equilibrium yields, using Eq. 19 (May *et al*., 1979):

$$N^*(F_N, F_P) = \frac{m + F_P}{e\ a}, \quad P^*(F_N, F_P) = \frac{r - F_N}{a} \tag{19}$$

At the unexploited equilibrium, net growth rates for both species drop to zero, leaving single species MSY undefined (May *et al.*, 1979). Operationally, management must ensure that every population maintains a positive effective growth rate amidst the regulated exploitation of its trophic counterpart. For the prey, holding predator at $\bar{P} < P^*$ through predator fishing gives an effective prey growth rate $r_{eff,N} = r - a\,\bar{P} > 0$. The surplus production model is operationalized under these reduced prey dynamics by implementing Eq. 20 (May *et al.*, 1979):

$$F_{MSY,N} = \frac{r - a\,\bar{P}}{2}, B_{MSY,N} = \frac{K_{eff,N}}{2}, MSY_N = \frac{(r - a\,\bar{P})K_{eff,N}}{4} \tag{20}$$

where $K_{eff,N}$ is the effective prey carrying capacity under background predation pressure $\bar{P}$. By parallel reasoning, maintaining prey at sub-equilibrium density $\bar{N} < N^*$ through prey fishing reduces the predator's net growth rate to $rr_{eff,P} = ea\,\bar{N} - m > 0$. Here, the effective prey carrying capacity is conditional on background predation pressure. Exploitation of the prey pool can depress abundance below unfished equilibrium levels, thereby constraining predator growth rates. Within this conceptual framework, the corresponding predator reference points are subsequently calculated using Eq. 21 (May *et al.*, 1979):

$$F_{MSY,P} = \frac{ea\,\bar{N} - m}{2}, B_{MSY,P} = \frac{K_{eff,P}}{2}, MSY_P = \frac{(ea\,\bar{N})K_{eff,P}}{4} \tag{21}$$

The predator reference points in Eq. 21 depend on background prey availability. Eqs. 20 to 21 therefore show that F_{MSY}, B_{MSY}, and MSY are conditional on trophic state rather than fixed biological constants. Augmenting predator exploitation can mitigate predation mortality and stimulate prey productivity, whereas increasing the extraction of prey populations restricts resource availability, leading to a corresponding decline in predator productivity. Consequently, optimizing one species can alter the reference points of another, and independently calculated single-species yields may not reproduce the system-level optimum (Mueter and Megrey, 2006; Walters *et al.*, 2005). The Lotka-Volterra formulation is too idealized for direct quantitative advice, but it demonstrates why ecologically significant predator-prey coupling can mis-specify single-species reference points (Andersen and Beyer, 2013). This result does not imply that every ecosystem-consistent fishing mortality must be lower than a single-species estimate or that summed single-species benchmarks, nor does it imply that cumulative single-species yield invariably surpass community-level optima. The direction and magnitude of adjustment depend on interaction strength, food-web structure, selectivity, environmental productivity, and management objectives (Walters *et al.*, 2005; Fulton *et al.*, 2022; Del Santo O'Neill *et al.*, 2024).

Example and Implication of MSY Implementation in towards Sustainable Fisheries

Empirical applications of MSY span a wide spectrum, from the data-rich, institutionally advanced fisheries of the North Atlantic and data-rich and data-limited fisheries. Rather than serving as statistically equivalent management units, the chosen case studies illustrate underlying ecological and institutional diversity. Given that these cases diverge across spatial scale, taxonomy, assessment method, and governance frameworks, cross-case comparisons are strictly bounded by five shared descriptive dimensions. These are data infrastructure, assessment methodology, harvest-control-rule enforceability, ecosystem awareness, and shared-stock governance. Case outcomes are not used to estimate prevalence or causal effects (Tabel 2). Additionally, the CMSY approach utilized in multiple data-limited instances has undergone continuous methodological refinement,

culminating in the CMSY++ implementation, which enhances the specification and empirical validation of catch-only priors against benchmark stock histories (Froese *et al*., 2023). Across the illustrative cases, data infrastructure, harvest rules bindingness, and multispecies/ecosystem awareness recur as important implementation dimensions. While fishery-independent surveys bolster analytical inference, standardized fishery-dependent observations and explicit uncertainty accounting can likewise underpin reliable scientific advice. Legally specified HCRs may reduce discretion, although outcomes still depend on compliance, enforcement, political economy, and ecosystem conditions. Where biological or technical interactions are intense, multispecies considerations assume critical importance. These findings represent descriptive signals extracted from a heterogeneous purposive sample, rather than direct measures of causal effect. The cases in Table 2 collectively reveal three recurring structural determinants of MSY implementation effectiveness, which are compared across geographic contexts in Table 3. Environmental pressures can alter MSY through biological and observational mechanisms. Warming can change growth, recruitment, natural mortality, distribution, and prey availability (Free *et al.,* 2019). Deoxygenation and acidification can reduce habitat quality and physiological performance (Breitburg *et al.,* 2018; Schmidtko *et al.,* 2017; Tai *et al*., 2021). Loss of reefs, mangroves, and seagrass can reduce carrying capacity or recruitment (Eddy *et al*., 2021; Lefcheck *et al.,* 2019). Trophic depletion can change effective productivity (Daskalov *et al.,* 2007; Walters *et al*., 2005), while discards, ghost fishing, and unreported catch add or conceal (Gilman *et al*., 2020; Richardson *et al*., 2019; Pauly and Zeller, 2016). These processes can alter *r, K*, recruitment, natural mortality, selectivity, interaction coefficients, or observation error. Consequently, operationalizing environmentally sustainable MSY mandates continuous parameter re-estimation, ecosystem indicators, strict habitat protections, and precautionary HCRs. The analyzed cases indicate that implementation outcomes are collectively shaped by underlying data infrastructure, institutional bindingness, and the incorporation of multispecies awareness. Fishery t-independent surveys can strengthen reference points relative to unstandardized commercial CPUE data, but the review does not establish data as the dominant causal constraint. Although binding rules effectively minimize management discretion, negotiated catches frequently surpass scientific recommendations, leaving conservation outcomes dependent on robust enforcement. Additionally, where predator-prey interactions are pronounced, explicit trophic adjustment become necessary (Walters *et al*., 2005; Del Santo O'Neill *et al*., 2024). An older evaluation of RFMOs found substantial governance gaps and depleted stocks (Cullis-Suzuki and Pauly, 2010), it is used only as a historical baseline, while the more recent fishery-specific evidence in Table 3 characterizes current institutional conditions.

Environmental implications for resource sustainability

MSY has direct environmental implications because fishing one trophic group can alter productivity in another. Predator depletion has caused cascading reorganization in the Black Sea (Daskalov *et al*., 2007), illustrating risks that may also arise in mixed fisheries when interacting stocks are managed independently (Walters *et al*., 2005; Del Santo O'Neill *et al*., 2024). Modifications of this nature can impair ecological resilience and erode the productive capacity underpinning food security and coastal livelihoods (Pauly *et al*., 2005; Pikitch *et al*., 2004). Climate and habitat pressures can compound these trophic effects. Empirical evidence indicates that ocean warming restricts fisheries productivity (Free *et al*., 2019), while accompanying deoxygenation and acidification processes drive structural shifts in habitat suitability and trophic networks (Schmidtko *et al*., 2017; Breitburg *et al*., 2018; Diaz and Rosenberg, 2008; Tai *et al*., 2021). Deoxygenation is particularly relevant to Southeast Asian waters (Kim *et al*., 2023). Furthermore, habitat degradation constrains carrying capacity and recruitment dynamics; global provisioning of coral reef ecosystem services has experienced widespread decline (Eddy *et al*., 2021), whereas

Table 2: Comparative synthesis of MSY application case studies from outside Indonesia and within Indonesia

No.	Species/ location	Assessment approach	MSY mechanism	Key findings	Identified weaknesses	Precautionary implications	Source
A. Applications outside Indonesia							
1	Atlantic cod (*Gadus morhua*) North Sea, Europe	VPA and SAM fitted to multi-decadal age-structured catch and acoustic survey data	EU CFP Reg. 1380/2013: mandatory F_{MSY} compliance by 2020; annual TAC set by European Union (EU) Council against ICES advice	Overfished stock share fell from about 74% (mid-2000s) to 26% (2020s); about 75% of Greater North Sea stocks are now below F_{MSY}, but North Sea cod itself remains overfished.	Single-species F_{MSY} on interacting mixed fisheries overestimates ecosystem-consistent yield (ΣMSYi); EU Council TACs have sometimes exceeded advice, though less often over time	F_{MSY} must function as a limit, not a target; multispecies trade-off models and multi-annual plans are needed to insulate advice from politics	Gras *et al.* (2024); ICES (2024); Del Santo O'Neill *et al.* (2024)
2	Northeast Arctic cod (*Gadus morhua*) Barents Sea Norway–Russia	SAM calibrated against >40 yr bilateral acoustic survey; F_{MSY} range 0.40–0.60	JNRFC bilateral HCR: ±20% TAC-change cap while SSB > Bpa; benchmark reassessment cycle	Record catches in the early 2010s; TAC cut 20% in 2024 (453,427 t) and 31% in 2025 (311,587 t); SSB fell below Bpa for the first time since 2002	±20% stability rule is suspended once SSB < Bpa, enabling larger 2025 cut; even so, the negotiated TAC stayed above advice; F_{MSY} stationarity breaks down under shifting productivity	More frequent benchmark assessments are needed under climate change; F_{MSY} should be time-varying; negotiated TACs should be more tightly bound to scientific advice, not just to the stability rule ceiling.	JRN-AFWG (2023) ;JRN-AFWG (2024)
3	Skipjack tuna (*Katsuwonus pelamis*) — Western and Central Pacific Ocean data period 1972–2024	8-region integrated stock assessment model; data 1972–2024; MSE framework for MP evaluation	CMM 2022-01 Management Procedure with explicit HCR and TRP; Management Procedure run set 2024–2026 effort limits (±10% cap)	Stock at about 98% of TRP (2024); catch record 2.1 Mt; $F/F_{MSY} \approx 0.35$; 0% overfishing risk; record catch about 2.1 Mt	Around 88% catch in Pacific Island EEZs, making revenue sharing as contested as biology; free-school sets suppress bigeye tuna; ENSO drives productivity variability beyond static MSY	±10% HCR guardrails limit abrupt effort change; needs better growth/age, tagging, and East Asia data	Teears *et al.* (2025)
4	Multispecies demersal pelagic complex (13 species groups) Gulf of Thailand, DoF 1971–2017	Non-equilibrium Schaefer and Fox surplus production models; aggregate system-level production model; supported by Ecopath-Ecosim model	Aggregate Multispecies MSY (MMSY) vs. sum of single-species MSYs (ΣMSYi); Thailand's TAC policy set at ~95% of aggregate MSY	MMSY only 65–80% of ΣMSYi; MMSY estimates highly sensitive to the baseline period chosen (degradation), recent states yield higher apparent MMSY, Fox model often fails for pelagics/long series, Schaefer more robust	ΣMSYi substantially exceeds MMSY; ecosystem degradation invisible in MSY-aggregate metrics; consistent catch-effort series	MMSY should complement, not replace, single-species checks (since ΣMSYi > MMSY); enforceable effort caps are essential; degraded systems need limit reference points below MSY; multispecies assessment should be prioritized where trophic and technical interactions are demonstrably strong	Fulton *et al.* (2022)

5	Kawakawa (*Euthynnus affinis*) Bay of Bengal Tamil Nadu, India 2001–2020	Multi-model: CMSY + BSM + SPiCT applied in parallel to 20-yr catch and CPUE data	No formal management procedure; assessment provides a reference point recommendation (effort reduction to achieve sustainable fishery)	All three models confirm overfishing and trend toward overfished state; models diverge quantitatively in h_{MSY} and F_{MSY} estimates	Model divergence quantifies the uncertainty envelope rarely reported to policymakers; no independent survey for validation; heterogeneous fleet complicates CPUE standardization	Where feasible, multi-model comparison can be used to characterize structural uncertainty in data-limited fisheries; uncertainty envelopes must be explicitly reported	Abinaya and Sajeevan (2025)
B. Applications in Indonesia							
6	Small pelagic aggregate Java Sea (FMA 712)	Schaefer and Fox surplus production models; CPUE from purse seine fleet; non-equilibrium biomass dynamics with risk analysis	TAC = 80% MSY; commodity FMA-specific reference points; FAO EAFM indicator integration	Sustained CPUE decline; production exceeds estimated MSY in successive years	Three biologically distinct species aggregated into one production unit; CPUE not standardized across heterogeneous fleet; systematic underreporting at informal landing sites	Species-level disaggregation is required as the minimum standard; GLM-based CPUE standardization essential; risk-analysis alongside MSY point estimates should become national practice	Suman *et al*. (2016, 2018); Sadhotomo and Admaja (2012); Zamroni *et al*. (2020); MMAF (2022)
7	Penaeid shrimp and demersal fish Arafura Sea (FMA 718)	Surplus production models; CMSY and BSM for post-moratorium reassessment	TAC = 80% MSY; moratorium on ex-foreign vessels (2014)	$B/B_{MSY} < 1.0$ and $F/F_{MSY} > 1.0$ for demersal groups, overfished, and actively overfishing; partial stock recovery observed post-moratorium	Industrial shrimp trawl bycatch largely unrecorded; small-scale fleet effort invisible in official statistics; surplus production models poorly suited to penaeid biology (ovigerous female selectivity)	Multispecies modeling of shrimp and demersal fish interactions is the minimum appropriate standard; fleet-wide data collection covering all segments is a prerequisite, not an optional improvement	Nurhakim (2004); MMAF (2022)
8	Multi-commodity national framework (11 FMA) Indonesia	CMSY and BSM alongside Schaefer/Fox; commodity- and FMA-specific assessments; FAO EAFM indicator frameworks	Kepmen KP 19/2022: 80% MSY TAC for 9 commodity groups in 11 FMA; procedural basis for licensing; integration into national SDG 14.4 monitoring	35/99 units overexploited; 53/99 fully exploited; national MSY estimate 12.01 Mt/yr; TAC 8.6 Mt/yr	Systematic underreporting of small-scale fleet effort; species aggregation masks within-group status heterogeneity; absence of formal uncertainty quantification in published reference points	80% MSY buffer is meaningful only with enforceable licensing caps; formal HCR linking assessment outputs to licence decisions is needed; multi-model uncertainty reporting should replace single-point MSY estimates in policy documents	MMAF (2022); Suman *et al*. (2016, 2018)

Note: VPA = Virtual Population Analysis; SAM = State-space Assessment Model; CMSY = Catch-based MSY; BSM = Bayesian State-space Schaefer Model; SPiCT = Stochastic Production in Continuous Time; HCR = Harvest Control Rule; TRP = Target Reference Point; TAC = Total Allowable Catch; F_{MSY} = Fishing Mortality at MSY; MMSY = Multispecies MSY; SSB = Spawning Stock Biomass; Bpa = Biomass at Precautionary Approach; JNRFC = Joint Norwegian–Russian Fisheries Commission; WCPFC = Western and Central Pacific Fisheries Commission; DoF = Department of Fisheries (Thailand); FMA = Fisheries Management Area; CPUE = Catch per unit effort; EAFM = Ecosystem Approach to Fisheries Management.

Table 3: Cross-contextual comparison of MSY implementation determinants between fisheries outside Indonesia and Indonesian FMA cases, with corresponding management implications

Dimension	Outside Indonesia	Indonesia	Management implication
Data infrastructure	Fishery-independent data dominate long-term acoustic/age-structured surveys, tagging programs, and observer systems	Fishery-dependent catch-CPUE only; no standardized survey; underreporting at small-scale/informal sites	Build fishery-independent surveys; mandate disaggregated, fleet-wide reporting
Assessment methodology	Spans age-structured models (SAM/VPA) to multi-model ensembles (CMSY+BSM+SPiCT) with explicit uncertainty reporting	Mostly aggregate surplus-production models (Schaefer/Fox/CMSY); uncertainty rarely reported	Use multi-model comparison where data and capacity permit; report uncertainty, not single-point MSY
HCRs	Legally binding HCRs	TAC = 80% MSY established (Decree of MMAF 19/2022 uniform across all stocks, no biomass-triggered adjustment)	Replace flat buffer with stock-specific, biomass-conditional HCRs linked to licensing
Multispecies and ecosystem awareness	Mixed-fisheries advice and ecosystem models in use (like Ecopath with Ecosim, MMSY vs. ΣMSYi)	Species/commodity aggregation masks individual stock status; no ecosystem model exists	Disaggregate species; pilot multispecies/ecosystem models for key mixed fisheries
Shared stock governance	Advanced bilateral/multilateral bodies (JNRFC, WCPFC) set shared-stock TACs	Domestic-only governance; access control, no shared harvest mechanism; limited Regional Fisheries Management Organization (RFMO) and WCPFC coordination.	Develop formal bilateral/regional cooperation for stocks linked to shared/migratory resources

mangroves and seagrass habitats remain essential for sustaining juvenile density and growth (Lefcheck *et al*., 2019). Fishing mortality can also be underestimated when discards, lost gear, small-scale catches, or unreported landings are omitted (Gilman *et al*., 2020; Richardson *et al*., 2019; Pauly and Zeller, 2016). Evidence from Indonesia similarly indicates a decoupling between habitat condition and fisheries productivity (Arthatiani *et al*., 2026), while deoxyribonucleic acid barcoding provides the resolution needed to detect biodiversity patterns obscured by aggregate biomass measures (Limmon *et al*., 2020). At ecosystem scale, catch-to-production ratios indicate widespread risk of ecosystem overfishing (Link and Watson, 2019), and climate-driven biomass losses can be amplified at higher trophic levels (Lotze *et al*., 2019). These findings support ecosystem-aware reference points and precautionary buffers (Säterberg *et al*., 2019; FAO, 1996). Mechanistically, thermal stress and deoxygenation lower intrinsic growth or carrying capacity parameters in production models; habitat loss shifts stock-recruitment parameters in stock-recruitment dynamics; and unmonitored extraction bias effective fishing mortality estimates upward. Rather than representing a fully coupled environmental model, these linkages remain conceptual, and comprehensive quantitative application to Indonesian fisheries management areas extends beyond the boundaries of this synthesis.

Toward a framework for assessing MSY implementation readiness

Tables 2 and 3 show that MSY implementation outcomes depend on structural determinants. ubsequently, this comparison is operationalized as a diagnostic tool that maps fisheries along a developmental gradient, moving from data-limited advisory MSY to institutionally sophisticated, ecosystem-consistent, adaptive and precautionary management, thereby highlighting the priority investments required to advance performance. The instrument converts the five features in Table 3 into an ordinal scale, applies it to the eight cases in Table 2, following the logic of tiered assessment frameworks already in use, notably the Australian Commonwealth Harvest Strategy Policy (Dowling *et al*., 2016) and the ICES stock data category scheme (ICES, 2021). This

progression corresponds with wider empirical evidence indicating that co-management frameworks involving both government authorities and resource users outperform strictly top-down regimes (Cinner *et al*., 2012). Additionally, composite indicates from small-scale Indonesian fisheries, such as an assessment of a coastal fishery in Biak Numfor, Papua, which exhibited strong economic performance alongside moderate habitat condition, imply that livelihood-oriented reforms frequently outpace ecological monitoring capabilities (Sakti *et al*., 2026).

Framework dimensions and scoring

Each dimension is scored at three ordinal levels, emerging, transitional, and advanced, with each score traceable to evidence in Table 2. In terms of data infrastructure, emerging management frameworks depend predominantly on unstandardized catch or CPUE metrics subject to underreporting, transitional systems incorporate multi-decadal catch-effort series or periodic survey; whereas advance regimes maintain sustained fishery-independent monitoring programs. Comparable tuna assessments illustrate the institutional and data investment required for advanced systems (Magnusson *et al*., 2023). In terms of assessment methodology, emerging systems rely on a single production model devoid of uncertainty quantification, transitional frameworks evaluate multiple models with partial uncertainty reporting; whereas advanced regimes employ age or size structured state-space models or management-strategy-evaluation-tested ensembles. For HCR enforceability, emerging regimes apply catch ceiling without biomass trigger, transitional regimes use stock-specific negotiated limits, and advanced regimes employ legally binding rules with explicit biomass triggers. For multispecies and ecosystem awareness, emerging regimes aggregate species without ecosystem modelling, transitional regimes estimate multispecies MSY alongside single-species MSYs, and advanced regimes use trophic model to adjust advice for interacting stocks (Del Santo O'Neill *et al.,* 2024; Walters *et al.*, 2005). Mechanisms for shared-stock governance vary along a continuum: spanning purely domestic management, regional coordination lacking binding authority and fully empowered bilateral or multilateral commission capable of fixing joint catch limits. Under equal weighting, the illustrative cases produce mean scores from 1.2 to 2.8. Although specific categorical assignments remain robust under alternative weighting parameters, numerous borderline cases undergo reclassification. Atlantic cod changes under the ecosystem-heavy scheme. Gulf of Thailand changes under the governance-heavy scheme. Kawakawa also shifts between emerging and transitional categories. This instability shows that the tier boundaries are not empirically validated. Accordingly, the empirical covariance between data quality and assessment performance is treated as a working hypothesis, leaving open whether data infrastructure constitutes the dominant limiting factor. Enforcement, governance, political economy, fleet structure, socioeconomic incentives, habitat degradation, and climate variability can independently limit performance.

Illustrative scoring and sensitivity

Under the equal-weight descriptive baseline, the eight illustrative cases yield composite scores reported in Table 4. These metrics merely summarize the compiled evidence without estimating actual management effectiveness, and the corresponding tier boundaries remain unvalidated thresholds. Equal-weight scores provide a descriptive ordering of the selected cases. Data-rich cases generally score infrastructure and assessment, while several Indonesian cases score lower on those dimensions. Because this covariance partially mirrors the criteria embedded in the scoring definitions, it cannot be taken as proof that data infrastructure serves as the overriding causal bottleneck. Enforcement, governance, political economy, fleet structure, socioeconomic

Table 4: Illustrative scoring of MSY implementation readiness across the case studies in Table 2

Case	Infrastructure	Assessment	HCR Enforceability	Ecosystem awareness	Shared Governance	Composite	Regime
Atlantic cod, North Sea (EU CFP)	3	3	2	2	3	13	Advanced, data-rich
Northeast Arctic cod (JNRFC)	3	3	3	2	3	14	Advanced, data-rich
WCPO skipjack tuna (WCPFC)	3	3	3	2	3	14	Advanced, data-rich
Gulf of Thailand multispecies	2	2	1	2	1	8	Transitional
Kawakawa, Bay of Bengal	2	2	1	1	1	7	Emerging, borderline
Java Sea small pelagic (FMA 712)	1	1	2	1	1	6	Emerging, data-limited
Arafura penaeid shrimp (FMA 718)	1	1	2	1	1	6	Emerging, data-limited
Indonesia national framework	1	1	2	1	1	6	Emerging, data-limited

incentives, habitat degradation, and climate variability can independently limit performance. Accordingly, prioritization should proceed via case-by-case evaluation, deploying expanded monitoring frameworks where operational conditions allow, and falling back on data-limited models where fishery-independent surveys are unfeasible.

Sensitivity of the classification to alternative scoring weights

Equal weighting is a baseline convention without independent empirical justification. Alternative weighting left the broad ordering of the highest- and lowest-scoring cases relatively stable but shifted several borderline classifications. Accordingly, the established category boundaries are inherently provisional. While sensitivity analysis mitigates concerns regarding weighting uncertainty, they do not supplant the necessity for systematic inter-rater testing or forma external validation.

Corroboration with findings reported elsewhere in literature

Table 5 summarizes literature that corroborates or qualifies themes identified in this review. Given that these studies share common elements with the underlying evidence base of the synthesis, the resulting comparison functions solely as functions solely as corroboration and does not provide an independent validation of the readiness framework. Corroborating evidence spans single-fishery cases (Chamera *et al*., 2025; Sakti *et al*., 2026) to global compilations (Zhou *et al*., 2012; Hilborn *et al*., 2020) and governance audits (Cullis-Suzuki and Pauly, 2010). While their alignment reinforces the credibility of several underlying themes, it does not constitute formal validation of the readiness heuristic. Although MSY remains a valuable heuristic when assumptions and uncertainties are transparently stated, multispecies dynamics and environmental variability can drive reference points in opposing direction. Consequently, the empirical case studies fail to identify one universally dominant management bottleneck.

Scope and limitations

The review and readiness framework has several limitations. No prospective systematic-review protocol, complete screening log, or deduplication record was available. The eight purposively selected cases differ in geography, management unit, data structure, model type, and period. It cannot support prevalence estimates or causal rankings. Given that the underlying heuristic was formulated from thematic elements also present within the selected cases, a certain level of circularity is inherent to the analysis. The five

Table 5: Corroboration of this review's key findings with evidence reported elsewhere in the literature

The present review finding	Independent evidence	Source
Trophic interactions can require different fishing mortality than single-species F_{MSY}; the direction is context dependent	Life-history synthesis links F_{MSY} to resilience traits, multispecies simulations report the same downward adjustment	Zhou *et al*., 2012; Walters *et al*., 2005
Data infrastructure and assessment sophistication cover in the illustrative cases, but causal dominance is not established	A data-limited Malawi assessment relied on catch-only proxies; CMSY++ development responds to the same global data gap	Chamera *et al*., 2025; Froese *et al*., 2023
Indonesia's 80% MSY-based TAC coexists with stocks independently found overfished	A small-scale Indonesian fishery index likewise found economic indicators outpacing ecological ones	Muawanah *et al*., 2018; Sakti *et al*., 2026
Binding HCRs improve outcomes but are insufficient without enforcement	About 50% of best-practice governance criteria, most managed stocks remain depleted	Cullis-Suzuki and Pauly, 2010
Active, science-based MSY management is linked to stock rebuilding, not collapse	Global stock-status compilations find actively managed fisheries rebuilding toward MSY-consistent biomass	Worm *et al*., 2009; Costello *et al*., 2016; Hilborn *et al*., 2020

dimensions are ordinal, equal weighting is only a baseline convention, and formal confidence ratings, inter-rater reliability, independent external validation are unavailable. Socioeconomic conditions, stakeholder legitimacy, market incentives, habitat state, and climate exposure are incompletely represented. The equilibrium and Lotka-Volterra derivations simplify stochastic, spatial, age-structured, technical, or climate-dependent dynamics. Accordingly, this framework functions strictly as a hypothesis generating instrument pending empirical testing on independent fisheries through formal inter-rater scoring, pre-determined weights, and calibrated confidence thresholds.

CONCLUSION

The reviewed evidence supports MSY as an analytical reference point rather than a fixed catch target. Equilibrium single-species models remain useful baselines, but their reliability declines when productivity, recruitment, habitat capacity, or species interactions change through time. While Schaefer, Pella-Tomlinson, and Fox formulations exhibit distinct production-curve shapes and reference points, age-structured and stock-recruitment dynamics introduce vital demographic detail. Furthermore, bioeconomic extensions account for market prices, operating costs, and fleet behavior, while precautionary reference points establish explicit safety buffers against assessment and implementation error, all of which are tested under uncertainty via. Multispecies and ecosystem approaches address interactions that single-species models cannot resolve. Predation, competition, prey availability, and technical interactions can shift sustainable exploitation levels upward or downward, so a universal adjustment to single-species fishing mortality is not supported. Environmental non stationarity further limits static reference points because warming, deoxygenation, acidification, and habitat degradation can alter growth, recruitment, natural mortality, distribution, or carrying capacity. Accordingly, routine stock reassessment, accompanied by state-dependent reference points where warranted, is mandatory to maintain management efficacy. The case synthesis also indicates that implementation depends on data quality enforcement, governance, fleet structure, market incentives, habitat condition and climate exposure. No single dominant constraint can be inferred from eight purposively selected cases. For Indonesian, standardized reporting, broader monitoring, fishery-independent information where feasible, and transparent data-limited methods can strengthen assessment. Harvest rules should also be linked to enforceable actions and periodically updated stock information. Operating as a tentative heuristic rather than a verified regulatory score, the readiness framework exhibits weighting sensitivity that underscores the requirement for independent validation and inter-rater reliability testing. Future research should

test climate-sensitive reference points, multispecies and single-species advice under realistic uncertainty, integrate socioeconomic and governance variables, and expand management strategy evaluation in data-limited tropical systems. In practice, MSY should be embedded within precautionary, adaptive, and ecosystem-aware management. Where ecological interactions play a critical role, ecosystem and habitat indicators ought to supplement stock-based reference points; concurrently, economic and livelihood targets should remain explicitly distinct from biological yield objectives. Management decisions should also be periodically revised as new ecological, climatic, and socioeconomic evidence becomes available through continuous monitoring and stakeholder engagement**.** This integrated approach provides a more defensible basis for productive fisheries, ecosystem resilience, and long-term environmental sustainability.

AUTHOR CONTRIBUTIONS

S. Triharyuni was responsible for conceptualizing the draft, searching the bibliography, selecting the relevant references, writing the initial manuscript draft, synthesizing the manuscript, and revising the final manuscript version. A. K. Supriatna was responsible for conceptualizing the draft, analyzing the references' coding, reviewing the whole manuscript, revising the final manuscript version and supervision. N. Anggriani was responsible for conceptualizing the draft, defining the bibliographic search, reviewing the whole manuscript, revising the final manuscript version and supervision. R. Puspasari was responsible for the work plan preparation, selecting the relevant references, reviewing the analysis in the manuscript, revising the final manuscript version and supervision.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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POSITIVE AI STATEMENT

During the preparation of this work, the authors used Claude Sonnet 4.6 Pro for assistance in drafting and refining the manuscript, which significantly improved the clarity and quality of the text. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

ABBREVIATIONS

%	Per cent
AFWG	Arctic Fisheries Working Group
B_{msy}	Biomass at maximum sustainable yield
Bpa	Biomass at Precautionary Approach
BSM	Bayesian State-space Schaefer Model
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CCSBT	Commission for the Conservation of Southern Bluefin Tuna
CFP	Common fisheries policy
CMM	Conservation and management measure
CMSY	Catch-based maximum sustainable yield
CPUE	Catch per unit effort
DNA	DeoxyriboNucleic Acid
DoF	Department of Fisheries (Thailand)
EAFM	Ecosystem Approach to Fisheries Management
EBFM	Ecosystem-Based Fisheries Management
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
Fig.	Figure
FMA	Fisheries management area
F_{msy}	Fishing mortality at maximum sustainable yield
HCR	Harvest Control Rule
ICCAT	International Commission for the Conservation of Atlantic Tunas
ICES	International Council for the Exploration of the Sea
IUU	Illegal, Unreported, and Unregulated
JNRFC	Joint Norwegian Russian Fisheries Commission
MEY	Maximum economic yield
MMAF	Ministry of Marine Affairs and Fisheries (Indonesia)
MMSY	Multispecies maximum sustainable yield
MSE	Management Strategy Evaluation
MSY	Maximum sustainable yield
OA	Open Access (bioeconomic equilibrium)
OY	Optimum sustainable yield
RFMO	Regional Fisheries Management Organization
SAM	State-space assessment model
SDG	Sustainable Development Goal
SPiCT	Stochastic production in continuous time
SPR	Spawning potential ratio
SSB	Spawning stock biomass
STECF	Scientific, technical and economic committee for fisheries
TAC	Total allowable catch
TRP	Target reference point
UNCLOS	United Nations Convention on the Law of the Sea
VPA	Virtual population analysis
WCPFC	Western and Central Pacific Fisheries Commission
WCPO	Western and Central Pacific Ocean
Y/R	Yield per recruit

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