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**Overview of Stock Assessment Methods and Management Measures Used for Squids and Other Short-Lived Species**

1. **Introduction**

Squids and other short-lived marine species play critical roles in marine ecosystems and global fisheries. These species typically have short lifespans, rapid growth rates, high natural mortality, and strong sensitivity to environmental variability. Their unique life-history traits, including semelparous or annual reproduction cycles, necessitate specialized approaches for accurate stock assessment and sustainable management. Conventional assessment methods developed primarily for long-lived fish species are inadequate for accurately capturing the dynamic population structure and rapid turnover characteristic of short-lived species (Arkhipkin et al., 2021).

Many fisheries targeting squids and other short-lived species face significant data limitations, commonly referred to as "data-poor" scenarios (Arkhipkin et al., 2021). "Data-poor" conditions arise when available information (often limited to catch and basic biological data) is insufficient to support traditional population models used to estimate biomass and fishing mortality. Complicating factors include variable natural mortality rates, short spawning periods, and the presence of multiple microcohorts within a year, each potentially differing in growth, maturation, and migration patterns (Brodziak and Hendrickson, 1999; Macy and Brodziak, 2001). High-resolution temporal (daily to weekly) and spatial data are required to identify cohorts accurately and effectively monitor population dynamics. Reliable age determination methods, such as statolith-based studies in squids, are critical since size alone is insufficient due to highly variable growth rates (Arkhipkin and Laptikhovsky, 1994). In the absence of comprehensive models, preliminary assessments often utilize analyses of spatiotemporal exploitation patterns, relative exploitation indices (e.g., catch-to-survey biomass ratios), and maturity indicators such as length at 50% maturity (Dunn, 1999; ICES, 2010).

Given these complexities, assessments and management strategies for squids and similar short-lived species commonly employ simplified, adaptive, and precautionary methods tailored specifically to their biological characteristics and environmental sensitivity.

1. **Stock Assessment Methods for Short-Lived Species**

**2.1 Empirical Indicators**

In many short-lived species fisheries, especially where comprehensive data are lacking, population status and exploitation trends are assessed primarily using empirical indicators. These include simple metrics such as commercial catch-per-unit-effort (CPUE) or catch data, mean body size, and length composition. Such indicators are widely used for monitoring interannual trends in abundance, shifts in size structure, and possible changes in recruitment (e.g., Zuur and Pierce, 2004; Chen et al., 2006; Georgakarakos et al., 2006). However, CPUE may not always be a reliable indicator of abundance, especially for species with patchy distributions, such as many squids (Winter and Arkhipkin, 2015). On the other hand, when fish are taken as bycatch, and provided that the spatiotemporal distribution of fishing effort is independent of fish abundance, a good relationship between abundance and CPUE is possible.

**2.2 Survey-Based Biomass Estimates**

Fishery-independent data have been used to derive recruitment indices and/or abundance or biomass estimates for a number of squid stocks globally (Sato and Hatanaka, 1983; Rowell et al., 1985; Augustyn et al., 1992; Roa-Ureta and Arkhipkin, 2007; Roa-Ureta and Niklitschek, 2007; NEFSC, 2011). Absolute or relative abundance or biomass of short-lived species such as squids is often estimated using swept-area calculations from bottom trawl surveys. These methods depend on catchability estimates, which are sometimes uncertain, so index-based approaches are used when catchability is unknown (Hendrickson and Showell, 2016). Estimation challenges arise when recruitment is prolonged and multiple intra-annual cohorts exist (Caddy, 1983), making age-based cohort identification and precise timing of recruitment pulses essential to avoid bias. The patchy spatial distribution typical of many squids can reduce survey accuracy, though stratified, random surveys conducted across the full geographic range of the species can help mitigate this issue (Arkhipkin et al., 2021).

Survey-based approaches are especially important when reliable fishery CPUE data are lacking, which is often the case in squid fisheries. For example, assessments like those for longfin inshore squid (*Doryteuthis pealeii*) in the Northwest Atlantic rely on seasonal stratified, random research bottom trawl survey data to estimate cohort-specific biomass and exploitation rates (Macy and Brodziak, 2001; NEFSC, 2011). Survey catchability uncertainty is addressed using prior distributions for survey parameters, and statistical techniques like GAMs improve standardization and precision (Jacobson et al., 2015). Biomass indices are typically compared to empirically derived targets and thresholds (e.g., 90% and 50% of carrying capacity, respectively) to guide quota management. However, direct estimation of f MSY-based fishing mortality reference points is often not possible due to data limitations, so the overfishing status of the stock could not be determined.

Another example is the northern shortfin squid (*Illex illecebrosus*) stock managed by the Northwest Atlantic Fisheries Organization (NAFO), where only landings and survey data are available. Here, annual relative biomass and mean body size indices from stratified surveys are used, and relative exploitation rates are estimated by dividing nominal catch by the biomass index (Hendrickson and Showell, 2016). The status of the stock is evaluated by comparing these metrics to long-term means across productivity regimes, and total allowable catch (TACs) is set using empirically derived proxies based on past peak catch and corresponding survey biomass indices.

**2.3 Yield-per-Recruit and Eggs-per-Recruit Models**

Yield-per-recruit (YPR) and eggs-per-recruit (EPR) analyses have been applied to semelparous short-lived species, such as squids, to estimate biological reference points (RPs; Hendrickson and Hart, 2006). These methods require detailed age-specific data, including natural mortality rates, individual weights, and gear selectivity. A key limitation of traditional per-recruit models is the assumption of constant natural mortality across ages, which is typically invalid for semelparous species whose natural mortality increases substantially post-spawning. Additionally, failure to incorporate age determination errors from methods such as statolith aging can significantly underestimate biological RPs like %MSP (percent maximum spawning potential) and MSY-based RPs (Hendrickson and Hart, 2006; Arkhipkin et al., 2021).

**2.4 Production Models**

Production models, including surplus production models, are used to estimate biomass and exploitation rates in short-lived species when time series data on catch and abundance indices are available (ICES, 2014; Meissa and Gascuel, 2015; Wang et al., 2016). These models relate population biomass to surplus production and removals by fisheries, allowing the estimation of management RPs such as BMSY and FMSY. For squids and other short-lived species, production models are typically applied in a state-space (dynamic) framework to better account for process and observation errors (ICES, 2014).

However, several limitations exist in applying production models to short-lived species (Arkhipkin et al., 2021):

1. The strong annual recruitment variability and short life span mean that the assumption of population equilibrium, which underpins traditional surplus production models, is often violated.
2. The models are sensitive to short time series and gaps in the abundance indices, which are common in cephalopod fisheries (Wang et al., 2016).
3. Estimation of productivity parameters and RPs can be highly uncertain if recruitment fluctuations are not properly accounted for (Meissa and Gascuel, 2015).

Despite these challenges, production models are still used in data-moderate situations to provide RPs for biomass and fishing mortality, especially when more detailed cohort or length-based models cannot be applied. Improvements in model structure, such as the inclusion of environmental covariates or hierarchical approaches, can help to partially address the limitations inherent in applying production models to short-lived species (Arkhipkin et al., 2021).

**2.5 Empirical Forecasting**

Empirical forecasting approaches are widely used for short-lived species such as squids to predict recruitment, abundance, or stock trends based on observed relationships with environmental variables and fishery-dependent or independent data. These methods typically rely on statistical correlations between indices such as sea surface temperature, productivity, or current regimes and measures of stock size or recruitment (Otero et al., 2008; Sobrino et al., 2020; Arkhipkin et al., 2021).

Although empirical forecasting provides flexible tools for management in data-limited situations, their reliability depends on the availability and quality of long-term datasets and careful validation of model relationships. When used alongside traditional stock assessment methods, empirical forecasting supports more responsive and ecosystem-informed management of short-lived species.

**2.6 Depletion Models**

Depletion models are particularly useful for assessing short-lived species with rapid population turnover, such as squids, by estimating changes in abundance within a fishing season based on high-frequency (e.g., daily or weekly) catch and effort data (Morales-Bojórquez et al., 2008; Winter and Arkhipkin, 2015). These models allow for real-time or near-real-time management responses. However, the intensive requirements for these data qualify depletion methods as data-rich.

***Depletion models with successive cohorts***

This approach tracks changes in abundance within each cohort throughout a fishing season. By monitoring successive cohorts as they enter and leave the fishery, the method estimates cohort-specific exploitation and abundance. This is especially relevant for species with extended recruitment periods and overlapping microcohorts, allowing for more accurate tracking of intra-annual dynamics (Paya ́, 2009; 2016; 2018).

***Generalized depletion models***

Generalized depletion models extend the basic depletion framework to accommodate the nonlinear processes in the relationships between catch rate and abundance and catch rate and fishing effort (Arkhipkin et al., 2021). These models can consider phenomena such as hyperstability and hyperdepletion (Harley et al., 2001) and saturability and synergy (Bannerot and Austin, 1983). Generalized depletion models are flexible tools that can simultaneously model data from multiple fishing fleets, with all parameters (except initial abundance and natural mortality) treated as fleet-specific (Maynou, 2015). These models can be applied at different temporal scales: intra-annual versions use high-resolution data within a single fishing season (daily or weekly), while multiannual versions operate on monthly data across multiple years or seasons. The ability to incorporate multi-fleet data and to analyze either short-term or long-term trends allows generalized depletion models to handle complex fisheries with variable effort patterns and extended time series (Maynou, 2015).

Depletion models are most effective when detailed, high-frequency data on catch and effort are available, enabling timely and responsive management decisions during the fishing season. Nevertheless, the reliability of depletion model outputs can be compromised by factors such as changes in catchability, fish movement or migration that are not accounted for in the model, as well as incomplete or delayed data reporting.

**2.7 Size-Structured Models**

Xu et al. applied a size-structured model to assess jumbo flying squid (*Dosidicus gigas*) in equatorial waters, in part due to the species’ short lifespan and the high cost of accurately aging individuals (Xu et al., 2018; 2019). Size composition data were grouped by month, and natural mortality was assumed to correlate with maturity, reflecting the species’ semelparous life history (i.e., all individuals die after spawning). The model depends on high-quality monthly size composition data, a monthly abundance index, and reliable growth information.

This approach represents an attempt to apply a relatively sophisticated modeling framework—typically used for long-lived species—to squid. Preliminary results demonstrated the model’s potential to capture key biological characteristics of jumbo flying squid, such as maturity-linked natural mortality. The monthly time step appeared suitable for modeling population dynamics, but the need for detailed monthly size composition data presents challenges for data collection. To date, this approach has not been further developed, and the results have not been used to inform management decisions.

**2.8 Integrated Ecosystem Assessments**

Integrated ecosystem assessments (IEAs) represent an approach that seeks to include not only traditional stock status, but also environmental conditions, ecosystem interactions, and external drivers into fisheries management decisions. For short-lived species like squids, which are strongly influenced by environmental variability and occupy important roles as both predators and prey, Arkhipkin et al. (2021) note that IEAs can help link changes in population dynamics with ecosystem indicators, such as shifts in predator and prey abundance or habitat conditions.

IEAs facilitate adaptive management by incorporating these broader ecological factors and linking population trends to external influences and have been implemented in two NAFO-managed Large Marine Ecosystems (Koen-Alonso et al., 2019). However, Arkhipkin et al. (2021) emphasize that the implementation of IEAs for short-lived species is challenged by the complexity of ecological interactions, limited data availability, and the need for interdisciplinary approaches. Furthermore, the inherent uncertainty and error in ecosystem-based models is typically much higher than in single-species assessments (Link et al., 2012). Despite these challenges, the development and integration of ecosystem-based approaches are recognized as increasingly important for the effective management of short-lived marine resources.

1. **Management Measures for Short-Lived Species**

Management of short-lived species, such as squids, presents unique challenges due to their rapid population turnover, high natural mortality, and strong sensitivity to environmental variability. The dynamic nature of these species means that conventional management tools developed for long-lived species may not be directly applicable. Instead, management strategies must be highly flexible and responsive to frequent and sometimes dramatic changes in abundance and recruitment.

Management approaches for short-lived species typically rely on a combination of input controls (such as effort limitation, gear restriction, and closed areas), output controls (such as total allowable catches), and additional measures like closed seasons or areas to protect vulnerable life stages (Arkhipkin et al., 2021). The unpredictable and fast-changing stock status necessitates regular monitoring and the ability to implement in-season adjustments. Precautionary and adaptive management frameworks are emphasized to prevent overexploitation and allow for rapid response to new data or changes in stock status.

**3.1 Reference Points**

For species with annual lifespans, such as many squids, stock assessments and RPs often need to be cohort-specific because maturation and growth rates can vary significantly among intra-annual cohorts and across years (Arkhipkin and Laptikhovsky, 1994). The type and quality of data available, as well as the biological relevance of the RPs to short lifespans, semelparous reproduction, and environmentally driven recruitment variability, determine the choice and applicability of RPs (Arkhipkin et al., 2021).

In data-rich fisheries—where catch, effort, and biological data are available at high temporal resolution—RPs can be estimated using analytical models, such as in-season depletion models (e.g., Arkhipkin et al., 2008; Roa-Ureta, 2012; Rosenberg et al., 1990; Winter, 2019). However, most managed squid stocks are data-limited, often relying only on landings and, at best, annual survey abundance or biomass indices, which are frequently derived from surveys not specifically designed for the species (Arkhipkin et al., 2021). For such stocks, formal estimation of RPs is much more challenging.

Globally, fisheries management often uses FMSY and BMSY as RPs (Zheng et al., 2019). However, for short-lived species, minimizing the risk of recruitment overfishing is a key objective. This is best achieved by ensuring that spawner escapement exceeds a minimum threshold (SSBmin) each year to safeguard recruitment; therefore, %MSP is often preferred over MSY-based RPs (Basson et al., 1996). However, per-recruit models—commonly used to estimate these RPs—are limited for squids due to the lack of cohort-specific age data and the assumption of constant natural mortality, which is inappropriate for semelparous species. Not accounting for age estimation errors and differences in mortality between spawning and non-spawning individuals can substantially underestimate %MSP- and MSY-based RPs (Hendrickson and Hart, 2006).

For data-poor stocks, biomass-based RPs are most used, as fishing mortality cannot be reliably estimated (Arkhipkin et al., 2021). For example, the NAFO-regulated northern stock of I. illecebrosus uses a BLim biomass threshold RP that does not assume specific stock dynamics and can be adapted for different productivity regimes (Hendrickson and Showell, 2016). Similarly, in Japanese management of Japanese flying squid (Todarodes pacificus), MSY-based RPs are estimated annually for each cohort using Beverton–Holt stock-recruit relationships and survey indices reflecting environmental regimes (Kidokoro and Mori, 2004).

**3.2 Effort-Based Management**

Effort-based management for cephalopod stocks was first proposed by limiting fishing effort to ensure that no more than 40% of available biomass is harvested each year (Caddy, 1983). This approach was first adopted in the Falkland Islands fisheries, where in-season monitoring enabled rapid adjustments to effort or closures when stock biomass approached management thresholds (Beddington et al., 1990; Rosenberg et al., 1990; Rodhouse et al., 2014). Managing by total allowable effort (TAE) offers benefits such as reducing catch misreporting and minimizing the race to fish (Beddington et al., 1990). However, the wider adoption of this approach has been limited by the difficulty in obtaining real-time fishery-dependent data required for effective depletion modeling (Augustyn et al., 1992; Brodziak and Rosenberg, 1993).

**3.3 Catch-Based Management**

Catch-based management, primarily through the use of TAC, has been more widely implemented than effort-based approaches (Baudron et al., 2010). TACs are generally established based on stock assessments that may employ a combination of methods—including catch-only models, surplus production models, and depletion models—to address uncertainties in stock structure and abundance (Rosa et al., 2013; Payá, 2016; Csirke et al., 2018). Scientific committees typically set annual quotas within defined ranges, informed by the results and uncertainties from these assessments.

Stock status is usually determined by comparing estimated biomass and fishing mortality rates to biological RPs such as BMSY and FMSY or their proxies. Management frameworks frequently include quotas, seasonal closures, mesh size restrictions, and bycatch limits. Regular scientific review of catch data and abundance indices is required, with recommendations made for adjusting Acceptable Biological Catch and TACs as necessary. Although TAC-based management provides a precautionary approach, its effectiveness is challenged by the high recruitment variability typical of short-lived species, often necessitating in-season adjustments and ongoing monitoring.

**3.4 Additional Management Measures**

Alongside TAC and TAE, a range of additional management strategies—such as spatial and temporal restrictions, mesh size requirements, and individual transferable quotas—are utilized in squids and other short-lived species fisheries to help reduce competitive fishing (Boyle and Rodhouse, 2005). Some fisheries have also achieved sustainability certification, although current evaluation standards are not specifically designed for short-lived, semelparous species. Spatial closures are used to protect juvenile and spawning squids, with the location and duration of closures varying annually in response to environmental conditions. Certain inshore spawning and nursery areas are designated as permanent marine protected areas, helping to maintain stock sustainability and prevent overfishing during years of low abundance (Arkhipkin et al., 2008; Arkhipkin et al., 2015).

1. **Conclusion**

The management and assessment of squids and other short-lived species demand approaches that reflect their distinctive biological and ecological characteristics. Traditional methods developed for long-lived species often underestimate the rapid population turnover, recruitment variability, and environmental sensitivity that define short-lived species. In response, fisheries science has adopted a diverse toolkit—ranging from empirical and survey-based assessments to depletion and production models—tailored to the data constraints and life-history traits of these species.

Successful stewardship of short-lived resources depends on flexible, adaptive management frameworks that can accommodate uncertainty and respond swiftly to fluctuations in stock status. This includes setting biologically relevant RPs, applying precautionary controls, and maintaining a capacity for in-season adjustments. As environmental change and data limitations persist, further integration of ecosystem considerations and development of rapid assessment methods will be essential to support sustainable exploitation and resilience in these dynamic fisheries.

**Table 1.** Examples of stock assessment methods for squids and similar short-lived species.

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| **Methods** | **Stock** | **Data type** | **Data details** | **Time step** | **RPs** | **References** |
| Catch-only | Jumbo flying squid (*Dosidicus gigas*) in Chile | Poor | Fishery catch | Year | BMSY, FMSY | Clark et al. 2014 |
| Index based | NAFO-regulated northern shortfin squid (*Illex illecebrosus*) | Poor | Fishery-independent  Mean body weight | Year (by cohort) | BLim | Hendrickson and Showell 2016 |
| Swept-area | Longfin inshore squid (*Doryteuthis pealeii*) in the Northwest Atlantic | Poor | Fishery independent  Trawl position, swept-area | Synoptic (by cohort) | BMSY proxy | NEFSC 2011 |
| Per-recruitment models | NAFO-regulated northern shortfin squid | Rich | Spawning age  Natural mortality-at-age  Mean weight-at-age  Fishery selectivity-at-age | Week | F50%, F40%, F0.1, FMax | Hendrickson and Hart 2006 |
| Production models | Western winter-spring cohort neon flying squid (*Ommastrephes bartramii*) in the Northwest Pacific Ocean | Rich | Fishery catch  Abundance index | Year | BMSY, FMSY | Wang et al. 2016 |
| Empirical forecasting | Octopus (*Octopus vulgaris*) in the Gulf of Cadiz | Poor | Environmental indices  Recruitment index | Year | BLim | Sobrino et al. 2020 |
| Depletion models | Western winter-spring cohort neon flying squid in the Northwest Pacific Ocean; Patagonian longfin squid (*Doryteuthis gahi*) in the Falkland Islands | Rich | Fishery CPUE  Individual weight  Maturity | Day  Week  Year | %MSP | Cao et al. 2014; Winter and Arkhipkin 2015 |
| Size-structured model | Jumbo flying squid (*Dosidicus gigas*) in the equatorial waters | Rich | Fishery CPUE  Size at catch | Month | NA | Xu et al. 2018 and 2019 |

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