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A Surplus Production Model for Sustainable Management of Anchovies (*Stolephorus* sp.) in the Fisheries of Larangan Waters, Tegal

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ABSTRACT

The surplus production model is a mathematical framework used to evaluate fish stocks and to determine the maximum sustainable catch. This model is an important tool for supporting sustainable fishing practices. Anchovy fishing in Tegal, Central Java, faces serious challenges due to indications of overfishing. The level of anchovy resource utilization has exceeded the maximum sustainable yield (MSY), and the optimal fishing effort level (fopt) has also been exceeded. In addition, fisheries management is considered ineffective due to a lack of adequate data and policies that are unable to limit fishing effort. This study aimed to identify the most appropriate surplus production model and to determine the maximum sustainable yield (MSY), utilization rate, and fishing effort level for anchovy in Larangan Waters, Tegal. The method used is descriptive analysis utilizing secondary data, including catch, fishing effort, and catch per unit effort (CPUE) from 2019 to 2023. The data were analyzed using regression tests from several surplus production models, Schaefer, Fox, Schnute, and Walter-Hilborn models. The best model was determined based on the R-squared value and the significance of the regression coefficients. The results indicate that the Walter-Hilborn model is the most appropriate, with an R^2 value of 0.964 and a significance level of $f < 0.05$. Based on this model, the optimal fishing effort (E_{MSY}) is estimated at 6.786 trips/year, and the maximum sustainable catch (C_{MSY}) is estimated at 948.228 kg/year. Data analysis show that fishing effort in Tegal has exceeded sustainable limits since 2021, reaching 117,38% and scalating to 144,31% in 2023. This trend confirms the presence of overfishing, requiring a strategic management approach to regulate fishing activies and number of fishing gear.

INTRODUCTION

The surplus production model is a mathematical framework that combines biological processes such as growth, recruitment, and mortality to assess fish stocks and determine the maximum sustainable catch **(Fulanda *et al.*, 2011; Chaboud, 2014; Sant'Ana *et al.*, 2017; Sumaila & Munro, 2019; Harlyan *et al.*, 2022; Rehatta *et al.*, 2022)**. This model is used for sustainable resource management by setting appropriate utilization levels to maintain ecosystem balance, economic optimization by determining the optimal point between fishing effort and catch to maximize benefits, and efficient production planning by considering environmental and economic factors **(Teniwut & Marimin, 2013; Sant'Ana *et al.*, 2017; Zainun *et al.*, 2019; Harlyan *et al.*, 2022; Rehatta *et al.*, 2022; Wiadnya *et al.*, 2023; Liu *et al.*, 2025)**. The advantages of using the surplus production model include the ability to integrate various data, flexibility in application across different ecosystems, and effectiveness in accurate stock research **(Nielsen *et al.*, 2017; Pedersen & Berg, 2017; Johnson & Cox, 2021; Mamdouh-Lotfy *et al.*, 2025)**. However, this model has limitations, including uncertainty in predictions, challenges in addressing extreme population fluctuations, and implementation complexity that requires a deep understanding of biological and environmental factors. Nevertheless, this surplus production model serves as a tool to ensure sustainable fisheries **(Mainardi, 2010; Link *et al.*, 2012; Omori *et al.*, 2016; Pedersen & Berg, 2017; Johnson & Cox, 2021)**.

The surplus production model has various types of models such as the Schaefer, Fox, Schnute, and Walter-Hilborn models. The Schaefer model is the simplest and most commonly used model due to its simplicity, but its estimates are less accurate when water conditions are not uniform **(Chaboud, 2014; Wang *et al.*, 2014; Mardhatillah *et al.*, 2019; Sumaila & Munro, 2019; Alawi & Dutta, 2023)**. The Fox model is more flexible and typically provides good results in complex fisheries with various fish species **(Nesslage & Wilberg, 2012; Chaboud, 2014; Susilowati *et al.*, 2016; Noman *et al.*, 2019; Sumaila & Munro, 2019; Ali *et al.*, 2022)**. Additionally, the more advanced Schnute model is suitable for fisheries with limited data, because it can adapt to various fish growth patterns **(Brunel *et al.*, 2010; Dickey-Collas *et al.*, 2014; Luquin-Covarrubias & Morales-Bojórquez, 2021; McDonald *et al.*, 2021)**. The last Walter-Hilborn model combines economic and biological factors, helping to find a balance between the benefits of fish catches and the health of the environment **(Pelletier & Mahévas, 2005; Pelletier *et al.*, 2009; Karp *et al.*, 2023; Azevedo *et al.*, 2024)**. All four models can be used for anchovy fisheries, but the Fox model is the most recommended option. This model is considered the most suitable due to its ability to adapt to various types of data, especially in fisheries that catch more than one species of fish. The Fox model better explains changes in catch data compared to simpler models like Schaefer **(Nesslage & Wilberg, 2012; Panhwar *et al.*, 2012; Karim *et al.*, 2018; Wiadnya *et al.*, 2023)**. However, if sufficient data are available, the Walter-Hilborn model becomes a better choice. This model offers a more comprehensive management framework, as it considers not only biological aspects but also important economic aspects for sustainable fisheries **(Somarakis *et al.*, 2004; Pelletier & Mahévas, 2005; Giannoulaki *et al.*, 2014)**. The Schaefer model can still be used due to its simplicity, especially when data are limited, although its weaknesses in changing environmental conditions should be noted **(Nesslage & Wilberg, 2012; Wang *et al.*, 2014; Karim *et al.*, 2018)**. The Schnute model is not recommended due to its complexity and high data requirements, which may not be practical for anchovy fisheries **(Walters *et al.*, 2008; Nesslage & Wilberg, 2012; Wang *et al.*, 2014; Naufal *et al.*, 2019)**.

Anchovy fisheries require attention due to their significant ecological and economic roles. Ecologically, anchovies play a crucial role in the pelagic food chain, connecting lower and upper trophic levels. They are primary consumers of plankton and serve as food for other species. A decline in anchovy populations can disrupt the balance of marine ecosystems **(Galatchi *et al.*, 2015; Albo-Puigserver *et al.*, 2016; Ventero *et al.*, 2017; Kamaluddin *et al.*, 2023; Moon & Kim, 2024)**. Additionally, from an economic perspective, anchovy is an important commodity for small-scale fishermen as a primary source of income supporting their livelihoods and well-being **(Mendonça & Sobrinho, 2013; Kamaluddin *et al.*, 2023; Wiadnya *et al.*, 2023)**. If anchovy fisheries are not properly managed, there is a risk of overfishing, leading to a decline in anchovy populations, ecological imbalance, and the threat of livelihood loss for fishermen **(Warningsih *et al.*, 2020; Kamaluddin *et al.*, 2023; Wiadnya *et al.*, 2023)**. The anchovy fishing sector in Tegal, which is one of the highest producers of fisheries in Central Java with *Stolephorus indicus* (Teri Jawa) and *Stolephorus commersonnii* (Teri Nasi) **(Sutono & Susanto, 2016; Imron *et al.*, 2020; Wiadnya *et al.*, 2023)** as its primary commodity due to the presence of the Jeruk coral reef in Larangan, which serves as a feeding ground, spawning site, and nursery for anchovies, is currently facing serious issues that threaten its ecological and economic sustainability **(Sutono & Susanto, 2016; Dewantara *et al.*, 2020; Kusnandar *et al.*, 2022; Kamaluddin *et al.*, 2023; Mulyani *et al.*, 2024)**. Ecologically, this fishery shows signs of overfishing, where the catch per unit effort (CPUE) from 1999 to 2011 decreased by an average of 11.24% per year, indicating a decline in fish abundance despite the increase in total fish production. The level of utilization of anchovy resources has exceeded the maximum sustainable yield (MSY) and the optimal fishing effort **(Sutono & Susanto, 2016)**. Economically, the performance of the fishery is considered poor due to excessive fishing capacity, price fluctuations, and management that is not based on the concept of maximum economic yield (MEY) **(Kamaluddin *et al.*, 2023)**. However, financial analysis indicates that anchovy fishing operations in Tegal still remain profitable. Additionally, the specifications of fishing gear and operational methods used are in line with current guidelines **(Kusnandar *et al.*, 2022)**. The main issue faced is ineffective management, as evidenced by insufficient data and policies that have failed to limit fishing efforts. Fishermen also recognize the importance of regulations and sanctions to address overfishing **(Kamaluddin *et al.*, 2023)**. These challenges require more planned and sustainable management using a surplus production model. This model can evaluate fish stock conditions using catch data and fishing effort to estimate various biological parameters **(Sutono & Susanto, 2016)**. Therefore, this study aimed to identify the most appropriate surplus production model, as well as determining the maximum sustainable yield (MSY), utilization rate, and fishing effort level for anchovy in the Larangan Coastal Fisheries, Tegal.

MATERIALS AND METHODS

The method used in this study is a descriptive analysis method that includes secondary data fish landing records at the Larangan Fish Landing Port in Tegal Regency (Fig. 1). The data collected between 2019 and 2023 directly correspond to catches of anchovy (*Stolephorus* sp.) using Payang and Puring fishing gears. These data are a result of fishing activities conducted in the adjacent Larangan Waters, recognized for the Karang Jeruk coral reef that nurtures anchovy populations. Since fishing effort is measured based on the number of boats departing, with two different types of fishing gear used, fishing gear standardization is necessary. This aims to ensure consistency and accuracy in calculating total fishing effort, especially since Puring fishing gear is more dominant in catching anchovies. According to **Gulland (1983)**, the standardization process is carried out in the following steps:

1. Determining Standard CPUE
   The standard fishing gear used is the Puring, as it has complete data and the highest CPUE (Catch per Unit Effort).
2. Calculating the fishing power index (FPI)
   The FPI for each fishing gear is calculated by comparing it's CPUE to the CPUE of the standard fishing gear (Puring). The FPI for Puring itself is 1.
   $$FPI_i = CPUE_r/CPUE_s$$
   Where, $CPUE_r$ is the CPUE of the fishing gear to be standardized, $CPUE_s$ is the CPUE of the standard fishing gear (Puring).
3. Calculating total standart effort

The calculated FPI value is used to determine the total standard effort (E) using the equation:

$$E = \sum_{i}^{k} FPI_i E_i$$

Where, E is the total standard fishing effort; E_i is the fishing effort of each gear; and k is the total of fishing gear used (k).

After standardizing the catch effort, this effort data, along with catch and CPUE data, is used as input for regression analysis in various surplus production models (SPM). The estimation models to be analyzed and evaluated include the Schaefer, Fox, Schnute, and Walter-Hilborn models. The statistical evaluation results (R^2) values and significance of regression coefficients will determine the best model as an estimator. The best model will be used to calculate the maximum sustainable catch (C_{MSY}), the optimum fishing effort (E_{MSY}), the utilization rate, and the exploitation rate of anchovy resources **(Gulland, 1983)**.

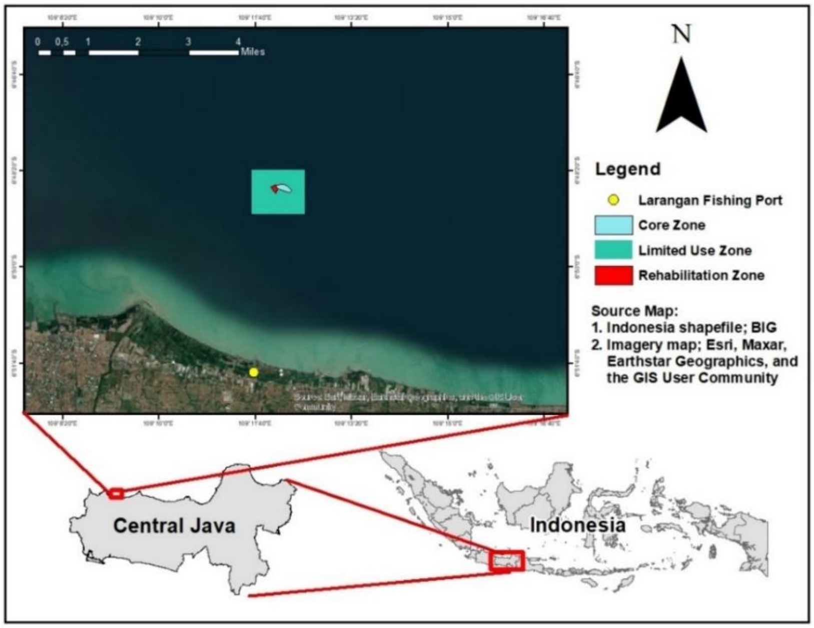

Fig. 1. Research map

Schaefer model

The Schaefer surplus production model in **Gulland (1983)** describes a logistic growth model as follows:

$$\frac{dB_t}{dt} = G(B_t) = r\,B_t\left(1 - \frac{B_t}{K}\right) \quad (1)$$

This equation does not account for consequences, so it is reformulated as:

$$\frac{dB_t}{dt} = r\,B_t\left(1 - \frac{B_t}{K}\right) - C_t \quad (2)$$

Where, K is the carrying capacity of the aquatic environment, and C_t is the catch, which can be written as follows:

$$C_t = qE_tB_t \quad (3)$$

Where, q is the catchability coefficient, and E_t denotes fishing effort. The equation can be formulated as:

$$\frac{C_t}{E_t} = q\,B_t = CPUE \quad (4)$$

From equation (2), the optimal catch can be calculated at $\frac{dB_t}{dt} = 0$ or referred to as the equilibrium point, which is formulated as:

$$r\,B_t\left(1 - \frac{B_t}{K}\right) - C_t = 0\text{, or } C_t = r\,B_t\left(1 - \frac{B_t}{K}\right) = qE_tB_t \quad (5)$$

Equations (3) and (5) yield the value of B_t as follows:

$$B_t = K\left(1 - \frac{qE_t}{r}\right) \quad (6)$$

thus equation (5) becomes:

$$C_t = q\,K\,E_t\left(1 - \frac{qE_t}{r}\right) = q\,K\,E_t - \frac{q^2K}{r}E_t{}^2 \quad (7)$$

Equation (7) can be simplified further to:

$$\frac{C_t}{E_t} = a - b\ E_t \text{ or } C_t = aE_t - bE_t^{\ 2} \quad (8)$$

Where, $a = q\ K$, and $b = \frac{q^2 K}{r}$.

This linear relationship is used to calculate C_{MSY} by determining the initial derivative of C_t for E_t to find the optimal solution, both for catch and fishing effort. The initial derivative of C_t for E_t is $\frac{dC_t}{dE_t} = a - 2b\ E_t$, thus obtaining the estimated E_{MSY} (optimal fishing effort) and C_{MSY} (maximum sustainable catch):

$$E_{opt} = \frac{a}{2b} = \frac{r}{2q} \quad (9)$$

By substituting the value of E_{MSY} into equation (8), the value of C_{MSY} is obtained as follows:

$$C_{MSY} = aE_t - bE_t^{\ 2} = a\left(\frac{a}{2b}\right) - b\left(\frac{a}{2b}\right)^2 = \frac{a^2}{4b}$$

By substituting $a = qK$, and $b = \frac{q^2 K}{r}$, will obtain:

$$C_{MSY} = \frac{a^2}{4b} = \frac{q^2 K^2}{4q^2 K/_r} = \frac{rK}{4} \quad (10)$$

The values of a and b are estimated using the least squares method to estimate the coefficients of the simple regression equation. Next, by substituting the value of E_{MSY} into equation (6), the optimal biomass (B_{MSY}) can be determined as follows:

$$B_{MSY} = K - \frac{Kq}{r} E_{opt} = K - \frac{Kq}{r}\left(\frac{r}{2q}\right) = K - \frac{K}{2} = \frac{K}{2} \quad (11)$$

The values of q, K, and r can be calculated using the Fox algorithm as follows:

$$q_t = \ln\left[\left|zU_t^{-1} + \frac{1}{b}/zU_{t+1}^{-1} + \frac{1}{b}\right|\right]/(z) \quad (12)$$

Where, $z = \left(\frac{a}{b}\right)/E^*$,$E^* = (E_t + E_{t+1})/2$,$U = \frac{C_t}{E_t}$, and q is the geometric mean of the values of q_t. From the values of a, b, and q, the values of K and r can then be calculated.

Fox model

Fox (1970) has different characteristics from the Schaefer framework. The decline in the catch per unit effort (CPUE) with respect to fishing effort (E) follows a negative exponential pattern.

$$C_t = E_t . \exp^{(a - bE_t)} \quad (13)$$

The optimal effort can be obtained by setting the first derivative of C_t with respect to E_t to zero:

$$E_{opt} = \frac{1}{b} \quad (14)$$

The maximum sustainable catch (C_{MSY}) is derived by integrating the optimal effort value into equation (13), resulting in:

$$C_{MSY} = \frac{1}{b} e^{a-1} \quad (15)$$

Schnute model

Schnute (1977) is a dynamic and deterministic variant of the surplus production model, interpreted as a modification of the Schaefer model.

$$\ln\left(\frac{U_{t+1}}{U_t}\right) = r - \frac{r}{qK}\left(\frac{U_t+U_{t+1}}{2}\right) - q\left(\frac{E_t+E_{t+1}}{2}\right) = a - b\left(\frac{U_t+U_{t+1}}{2}\right) - c\left(\frac{E_t+E_{t+1}}{2}\right) \quad (16)$$

Where, $a = r$,$b = \frac{r}{qK}$, , and $c = q$ are the estimators of the multiple regression coefficients.

Walter-Hilborn Model

Walter and Hilborn (1976) as cited in **Kekenusa *et al.* (2014)**, formulated an alternative surplus production model called the regression model, which uses a simple differential equation with the following equation:

$$\frac{U_{t+1}}{U_t} - 1 = r - \frac{r}{Kq}U_t - qE_t = a - bU_t - cE_t \quad (17)$$

Where, $a = r$, $b = \frac{r}{qK}$, and $c = q$ are the estimators of the multiple regression coefficients.

RESULTS

Annual anchovy (*Stolephorus* sp.) catches landed at Larangan TPI have experienced significant fluctuations (Table 1). The year 2021 was recorded as the year with the lowest catch, in contrast to the previous year, which was the peak. This pattern repeated in 2023, with catches declining after an increase in 2022. Despite fluctuations and declines in catches during certain periods, fishing efforts showed consistent increases each year.

Table 1. Data captured from 2019 to 2023

Year	Catch (kg)	Effort (trips)	CPUE $=\frac{C_t}{E_t}$ (kg/trip)
2019	856.975	4827	177,54
2020	1.131.847	5912	191,45
2021	676.127	7965	84,89
2022	1.012.676	9028	112,17
2023	895.685	9792	91,47
Average	914.662	7504,8	131,503

The data were analyzed using several surplus production models: Schaefer, Fox, Schnute, and Walter-Hilborn. The results of the regression tests for each model are summarized in Table (2).

Table 2. Regression test calculation results

Model	Regression Test			
	F-test	Sig f	R^2	Adjusted R^2
Schaefer model	9,359	0,055	0,757	0,676
Fox model	7,993	0,066	0,727	0,636
Schnute model	0,347	0,743	0,257	-0,485
Walter-Hilborn model	26,701	0,036	0,964	0,928

Based on the data presented in Table (2), the Walter-Hilborn model ($\frac{U_{t+1}}{U_t} - 1 = 4{,}03 - 0{,}014U_t - 0{,}0003E_t$) is the most appropriate model with an R^2 0.964 and a significance level f< 0.05, with values of a= 4.03 and b= 0.014. From the equations, the optimal catch effort E_{MSY} and maximum sustainable catch C_{MSY} can be calculated using equations (9) and (10). The values of E_{MSY} and C_{MSY} are obtained from the following calculations:

$$E_{MSY} = \frac{r}{2q} = 6.786 \text{ trips/year}$$

$$C_{MSY} = \frac{rK}{4} = 948.228 \text{ kg/year}$$

The value of E_{MSY} indicates the maximum effort in a year that does not exceed 6786 trips/year, while the value of C_{MYS} indicates the maximum amount of anchovy that can be caught 948.228 kg/year. Details regarding the percentage of fishing effort and utilization rates for anchovy each year can be seen in Table (3).

Table 3. Percentage of utilization rates and efforts

Year	Utilization Rate (%)	Effort Level (%)
2019	90,38	71,14
2020	119,36	87,13
2021	71,30	117,38
2022	106,80	133,05
2023	94,46	144,31
Average	96,46	110,60

Data for the five years (2019–2023) show two contrasting trends between resource utilization and capture effort. Resource utilization fluctuated, with the highest value recorded in 2020 at 119.36% and the lowest in 2021 at 71.30%. On the other hand, fishing effort shows a consistent and significant increase each year, surging from 71,14% in 2019 to 144.31% in 2023.

DISCUSSION

The most appropriate production surplus model for anchovy (*Stolephorus* sp.) fisheries is the Walter-Hilborn model ($\frac{U_{t+1}}{U_t} - 1 = 4{,}03 - 0{,}014U_t - 0{,}0003E_t$) with R^2= 0.964 and a significant level f<0.05, while the inappropriate model is the Schnute ($\ln\left(\frac{U_{t+1}}{U_t}\right) = 4{,}36 - 0{,}015\left(\frac{U_t + U_{t+1}}{2}\right) - 0{,}00033\left(\frac{E_t + E_{t+1}}{2}\right)$) with R^2= 0,257 and a significant level f> 0.05 (Table 2). **Wang *et al.* (2011)** and **Naufal *et al.* (2019)** explain that the Walter-Hilborn model is superior for anchovy fisheries, although the Schnute model is more robust against data errors and variability. The Walter-Hilborn model was selected because it provides a more comprehensive management framework by considering both biological and economic aspects. Conversely, the Schnute model is not recommended due to its complexity and high data requirements, which are impractical for anchovy fisheries. This is supported by research conducted by **Dewantara *et al.* (2020)** and **Zulkarnaini *et al.* (2022)**, who used the Walter-Hilborn model as the most suitable model for anchovy fisheries.

The Walter-Hilborn model equation obtained values of E_{MSY} 6786 trips/year and C_{MSY} 948.228 kg /year, which were presented as the level of fishing effort and utilization of anchovy each year (Table 3), showing signs of overfishing driven by overcapacity. This is in line with research by **Sutono and Susanto (2016)**, **Dewantara *et al.* (2020)**, **Kusnandar *et al.* (2022)**, **Kamaluddin *et al.* (2023)**, **Wiadnya *et al.* (2023)** and **Mulyani *et al.* (2024)**, which found that Tegal experienced overfishing with an increase in fishing effort, but catch yields or CPUE show a declining trend, and the utilization rate of anchovy resources has exceeded the sustainable potential limit. This increased fishing effort is driven by the relatively high market price of anchovy, prompting fishermen to continue seeking maximum yields. The local community's dependence on this resource also drives continued exploitation, despite the depletion of anchovy stocks. Although the fishing gear used complies with technical guidelines, it has the potential to catch small fish, non-target species, and juvenile fish from other species that can damage the ecosystem. The lack of regulations limiting the number of fishing gear and allocating vessels permitted to operate is one of the causes. Fishermen themselves acknowledge the need for regulations in the form of restrictions on the number of fishing gear and the division of fishing areas (zoning). Efforts to address this issue include controlling fishing and the number of fishing gear used, dividing fishing zones to separate fishing areas with different types of fishing gear and avoid unhealthy competition, and implementing agreed sanctions to ensure compliance with management rules.

CONCLUSION

The Walter-Hilborn model was identified as the most suitable surplus production model for Larangan Waters anchovy (*Stolephorus* sp.) fishery. The result of this model analysis suggest the presence of overfishing, as a consistent increase in fishing effort each year has not led to corresponding sustainable growth in catch yield or the rate of resource utilization. Therefore, effective management is critical for the future sustainability of the fishery's resources.

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