A system dynamic of the harvesting strategies to sustain the population of squid using logistic growth model

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Abstract. Loligo Duvauceli, is known as squid in the local name. Squid is a species of high value and a good source of protein besides fish. In this paper, a logistic growth model with constant and periodic harvesting are used to find the optimum sustainable population of Loligo Duvauceli in order to preserve the resource. The data used for this study was obtained from Department of Fisheries. The aims of this study are to estimate to determine the stability of the equilibrium point. Then, the effect of the constant and the periodic harvesting on the population of squids analysed. Finally, to compare the results obtained between the two strategies. The best harvesting selected squids is periodic harvesting.

1. Introduction
Squid is one of the living cephalopods that comes from the ancient group of Molluscs [1]. According to [2], the scientific name for squid is Loligo Duvauceli. It is also known as Sotong in the local name. There are approximately 700 species of cephalopods have been identified in the world [1].

According [3], the ocean holds approximately about 500 species of squids. Cephalopods species are commonly found in South China Sea and other adjacent sea areas including the Northern end of South China Sea for South Asian countries [1]. However, the South China Sea has the lower diversity of cephalopods than in the Japanese seawater.

Squid hatching occurred between February and August with the peak in the austral winter/spring and another smaller peak in the austral summer has been counted their age using the statolith micro increments and back-calculation from the date of they are captured [4]. The squid’s presence is seasonal, but difficult to predict [5]. Squid’s eggs are covered with the gelatinous capsules or masses and their eggs are abandoned after they are spawning, usually in large numbers. Fisherman all over the world harvest squid by trawling, seining, trap fishing, pot fishing, gill net fishing and jiggling [6].

Squid harvesting plays important role in fishing industry because of its demand in the market. Market squid are an important species to the coastal pelagic species fishery. The market squid resource
is a monitored species, which means their landings and available abundance indices are considered sufficient to manage the stock. About 7.5% of the total catches by trawlers in the Gulf of Suez are dominated by cephalopods by which 5% are cuttlefish and 2.5% are squids [7].

The Northwest Pacific dominates the squid catches in 1990, which is 44 percent of the world squid harvest [8]. About 48 percent is catches by Japanese vessels. Southwest Atlantic becomes the second global squid landings, which is 31 percent. The Republic of Korea, Russia, Japan and Chine take 72 percent from the landings, while Spain, Argentina, Poland and Germany taken the balance of it. Meanwhile, 6 percent of squid landings is in Western Central Pacific becomes the third place in the world. Thailand, the Philippines, Indonesia and Malaysia conquered the squid harvesting.

The major fish group in the Malaysia fisheries, which account five to six percent of the total fish landings, goes to cephalopods [9]. The information on their biology, distributions and migrations activities is scarce compared to the finfishes. The dominant squid species in Malaysian water are Loligo duvaucelli, Loligo chinensis and Loligo singalensis. The squids in West Coast of Peninsular Malaysia areas are more abundant compared to the East Coast of Peninsular Malaysia. Loligo Duvaucelli is the squid species that dominate the catch in West Coast. Squids are mobile and active species, which are highly migratory during their lifespan. The time and the period of study are closely related to their distribution, abundance and spawning activities.

A major current focus in fishery management is how best to ensure harvesting sustainability [10]. The suitable harvesting strategies will control the volume of the population and avoid them from extinction. The numerical simulations and qualitative analysis of six fisheries has been used to examine systematically the consequences of different harvesting strategies, which are proportional harvesting, threshold harvesting, proportional threshold harvesting, and seasonal and rotational harvesting. Each year, a fixed number of fish are remove by constant harvesting. On the assumption, the fisherman has perfect information on the location of the fish. The proportional harvesting removes a constant fraction of fish each year. Meanwhile, only a fixed proportion of the fish above the threshold are harvest by using proportional threshold harvesting. Rotationally, the field is been divided into different area and closes some of them by using the rotational harvesting. The numerical analysis will be almost the same as the periodic harvesting; the difference is just the closure period will likely to be longer and the fish population has more time to recover from the harvest season. In their study, the density effect of fish relies based on their new fishing effort model. It is prove that a larger amount of fish in certain period can be obtained by using rotational harvesting strategy.

There are many theories that have been invented with respect to long-lived species of fin-fished or marine mammals [11]. These marine creatures have exceeded their phase of maturation because they are not imposed to the exploitation. The harvested adult population is usually composed of a wide range of age classes so that any effects of fishing are spread across a number of cohorts. Differently to the finfish, species of cephalopods are short-lived and die soon after spawning so there is no overlap between generations. The starting point in examining the potential selective effects for the dynamics of squid species exposed to exploitation is been used as the assumptions of the life history optimization approach.

Sustainable development is often defined as development that satisfies current needs without risking the ability of future generations to satiate their own [12]. However, this definition is still a generalized concept, and is often criticized as being difficult to translate in operational terms. This study will use the system dynamics, which enhances learning in complex and non-linear systems behaviour over time, to assess the sustainability of marine protected areas [13-15]. Mathematics model have been used widely to estimate the population dynamics of animals for so many years as well as human population dynamics. The logistic growth model in term of harvesting has been used to study the squid population. A major goal for successful management of harvested population is to find harvesting strategy that are sustainable, not leading to instabilities or extinction and the result are large annual yield, with a little variation among years [16-19].

Harvesting has been an area under discussion in population as well as in community dynamics [20], [22]. Malthus was the first to formulate theoretical treatment of population dynamics in 1998 and
Verhulst formed the Malthus theory into a mathematical model called the logistic equation that led to nonlinear differential equation [23-25]. Harvesting has been considered a factor of stabilization, destabilization improvement of mean population levels, induced fluctuations, and control of non-native predators [26]. The objectives of this project are to determine the stability of the equilibrium point. Then, the effect of the constant harvesting and periodic harvesting on the squid population will be analysed.

2. Materials and Methods

2.1 System Dynamic Modelling

System dynamic developed by Professor Forrester from MIT in mid-1950s was applied in several research field [27-29]. While the analyses of economic models tend to depend on terminal conditions of the system and focus on the steady state, a system dynamic approach highlights the transition paths that is how the dynamics of a system changes over time.

The system dynamic model is an interconnected system of differential equations that could be simulated on varying the input of variable. To build a system dynamic model, we are making certain simplifying assumptions based on the constraints laid out in the squid population growth scenarios. This particular research method was chosen because system dynamics was widely used for economic, social and environmental studies as result as this particular method proven useful to reveal the dynamic changes, feedback and other variable cause and effect onto its particular area [30,31].

Population growth should be stable, that id near the carrying capacity. However, population should be not static.it would remain a little below or over the carrying capacity.

Figure 1. Flow diagram for harvesting Sector

A stack and flow diagram of the system dynamics model of this study can be seen in Figure 1. This model consists of the following of squid’s population dynamics. The squid population is contains of three sub model, there is young fishes, mature fish and harvest.

2.2 Squid Population Dynamics

The squid population model is based on the dynamic biomass (Gordon–Schaefer) model. Which states that the increase in young fishes due to reproduction is equal to the growth rate of squid multiplied by

...
the existing population, minus the natural decrease in squid multiplied by the ratio of squid matured to the squid stock carrying capacity. The logistic growth model can be written as:

\[
\frac{dP}{dt} = rP \left(1 - \frac{P}{k}\right)
\]

(1)

Here the variable \( P \) can be interpreted as the size of the population. Its development over time, \( P(t) \) depends on its initial value \( P(0) \) and on the two parameters \( r \) and \( K \), where \( r \) is called the rate of squid survive at maturity stage and \( K \) is referred to as the carrying capacity of the population.

The harvest squid population indicates the outflow squid, a result of catch [32]. Parameter \( H \) was introduced as harvesting function.

\[
\frac{dP}{dt} = rP \left(1 - \frac{P}{k}\right) - H(t)
\]

(2)

Two types of harvesting strategies were used, namely:

1. The logistic growth model with constant harvesting. In this case \( H(t) = h, h > 0 \).
2. The logistic growth model with periodic harvesting. In this case \( H(t) = h(1 + \sin(bt)) \).

Note that \( H(t) \) is a periodic function of time with the period of one year. The squid population will not be able to extinct in fishing time since \( H(t) \) is a periodic function and varies from season to season. The amount of squid might be able to increase again if in some season the fishing activity is stopped.

2.3 Collection of the data
Data has shown that, the number of licensed fishing gears by state, Perak has the highest volume compared to other places in West Coast which is 3,797 in totals. Record shows that 1,380 for trawls nets, 1,524 for drift/ gill nets, 536 for other seine and the balance are for other gears. Squid or *Loligo Duvaucelli* catch by trawls net is the highest in the record based on Landing of marine fish by gear group and species compared to other gear [33]. The data of squid for this research is obtained from Department of Fisheries. The data in Figure 2 shows the landing of squids in Perak for the years 1998-2011.

![Figure 2. the landing Squid in Perak for the year 1998-2011](image)

3. Result and Discussion
From section 2, the value of parameter growth rate, \( r = 0.7706 \) and carrying capacity, \( k = 12716 \). The equation is autonomous, it is possible to solve directly for equilibrium and bifurcation values.

3.1 Equilibrium solutions of the modified logistic growth model
The equilibrium point is called stationary or critical point. An equilibrium point of the logistic growth model is a point where is no change in the population. That is the population remain constant over time...
(also called the steady state). Thus, the equilibrium point for the growth model is either the trivial solution or the carrying capacity. The equilibrium point of the logistic growth solutions are given as follows:

\[ \frac{dP}{dt} = 0 \]

By setting, the equation (1) is equal to zero; we have the two-equilibrium solution.

\[ rP\left(1 - \frac{P}{k}\right) = 0 \]

Substitute the value of \( r \) and \( k \)

\[
0.17706P\left(1 - \frac{P}{12716}\right) = 0
\]

\[
0.17706P = 0
\]

\[
P = 0 ,
\]

And

\[
1 - \frac{P}{12716} = 0
\]

\[
\frac{P}{12716} = 1
\]

\[
P = 12716
\]

This means that if the initial population started with \( P = 0 \), population remains at \( P = 0 \). Similarly, if the initial population started with \( P = 12716 \), the population remains at the same level. Figure 3, shows the two values of equilibrium point namely \( P = 0 \) and \( P = 12716 \).

![Figure 3. Equilibrium point of the modified logistic growth model](image)

Divide the vertical line into three intervals,

1. \(-\infty < P < 0\)
2. \(0 < P < 12716\)
3. \(12716 < P < +\infty\)
$P = 0$ is an unstable equilibrium point because the solutions near this point are repelled. This means given an initial population $P_0$ just above $P = 0$ and the $P_0$ is less than 0, it is clearly seen that the population extinct. The equilibrium point at $P_0 = 12716$ is a stable equilibrium point because solutions near this point are attracted to it. This means given an initial population in the interval $(0, 12716)$, the population increase to a steady state 12716. If it is greater than 12716, the population declines and approaches a limiting values 12716 which is the carrying capacity.

Hence, the differential equation (1) is autonomous. So, the equilibrium solution are $(0) = 0$ and $(12716) = 12716$. Table 1 shows the intervals of equilibrium point that are showing whether the equilibrium point is stable or unstable.

| Interval                  | Sign | P(t) | Arrow          |
|---------------------------|------|------|----------------|
| $(-\infty, 0)$            | Minus| Decreasing | Point Down |
| $(0, 12716)$              | Plus | Increasing | Point Up   |
| $(12716, +\infty)$        | Minus| Decreasing | Point Down |

3.2 Logistic growth model with constant harvesting

The logistic growth model with constant harvesting as follows:

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{k}\right) - H(t)$$

(6)

where the value of $H$ is constant.

To determine the equilibrium points for $H$ is constant:

$$0.17706P\left(1 - \frac{P}{12716}\right) - H = 0$$

$$0.17706P - 0.17706P - H = 0$$

$$-0.000013924P^2 + 0.17706P - H = 0$$

(7)

By using square quadratic formula:

$$P = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$= \frac{-0.17706 \pm \sqrt{(0.17706)^2 - 4(-0.000013924)(-H)}}{2(-0.000013924)}$$

(8)

Consider the expressions under the square root sign. Letting this expression equals to 0, we have:

$$0.17706^2 - 4(-0.000013924)H = 0$$

$$0.03135 - 0.000055669H = 0$$

$$H = 562.87 \approx 563$$

(9)

When the value of $H = 563$ (known as bifurcation point) we consider 3 different values of harvesting:

1. $H = 563$
2. $H > 563$
3. $H < 563$

For $H = 563$, Figure 4 shows that there exists only one equilibrium point. For $P_0$ larger than 6358, the population will decrease and approach to 6358. For $P_0$ less than 6358, the population will lead to extinction.
Figure 4. Constant Harvesting, $H = 563$

Table 2 summarizes the result

| interval       | Sign  | P(t)     | Arrow         |
|----------------|-------|----------|---------------|
| $(-\infty, 6358)$ | Minus | Decreasing | Point Down    |
| $(6358, +\infty)$ | Minus | Decreasing | Point Down    |

For $H > 563$, the value of harvesting is $H = 610$, there is no real solution and there is no equilibrium points obtained. This is shown in figure 4. For any population taken, the population of squid will extinct. This shows that, fisherman cannot harvest more than carrying capacity, $k = 12716$ in order to preserve the species.
For Figure 5, the value of harvesting is $H = 610$. The figure indicates decreasing trend at any initial population of squid. This also implies that the population will go to extinct regardless of the population size. Table 3 summarizes the result.

**Table 3.** interval of equilibrium points for harvesting, $H = 610$

| Interval | Sign  | P(t) | Arrow          |
|----------|-------|------|----------------|
| $(-\infty, \infty)$ | Minus | Decreasing | Point Down |

For $H < 563$, the value of harvesting, $H = 500$. In this case, there are two equilibrium points namely $P = 4233$ and $P = 8483$. Figure 5 shows the solution curve for $H < 563$. When $H = 500$, two values of equilibrium point exist, namely $P = 4233$ and $P = 8483$. The lower equilibrium point at $P = 4233$ is unstable because the solution curve more away from it. This tells that with initial population less than 4233 and with constant harvesting that less than 12716, the population will extinct. If the population is taken between 4233 and 8483, the population of the squid will increase until it reaches the stable state. The upper equilibrium point is stable because if initial population is within interval $(8483, \infty)$ the population decrease to the point of $P$. 

**Figure 5.** Constant Harvesting, $H = 610$
Figure 6. Constant Harvesting, $H = 500$

Table 4 summarizes the result.

| Interval               | Sign  | $P(t)$       | Arrow           |
|------------------------|-------|--------------|-----------------|
| $(-\infty, 4233)$     | Minus | Decreasing   | Points Down     |
| $(4233, 8483)$         | Plus  | Increasing   | Point Up        |
| $(8483, +\infty)$      | Minus | Decreasing   | Point Down      |

3.4 Logistic growth model with periodic harvesting

Consider the logistic growth with periodic harvesting model:

$$\frac{dP}{dt} = rP \left(1 - \frac{P}{k}\right) - H(t + \sin(bt))$$  \hspace{1cm} (10)

The term $H(t) = h(t + \sin(bt))$ represents the contribution of the sine wave to the periodic function. In other words, it is the coefficient that dictates the total rate of periodic harvesting with the period of one year. The squid population will not be able to extinct in fishing time since $H(t) = h(t + \sin(bt))$ is a periodic function and varies from season to season. The amount of squid might be able to increase again if in some season the fishing activity is stopped.

Parameter $b$ represents the wavelength of the sinusoidal function that describes the periodic harvesting. The period of maturity for the squid is 120 days old [34]. By other words, the squid takes 4 months for to mature. Therefore, we used parameter $b = \frac{1}{3}$ in a year.

From logistic growth model without harvesting, we know that the equilibrium points are at 0 and 12716 if the sine function is not present. We need to find equilibrium point for periodic harvesting. In this case, logistic growth with periodic harvesting model is non-autonomous. Then, the equilibrium point for periodic harvesting can be found with numerical solution and result for equilibrium point with the help from MATLAB by using graphically.

In the logistic growth model with constant harvesting, we concluded that $H = 563$ is bifurcation point. With this function, we can only guess that bifurcation will occur at some value of a near 563.
As we know, the value for $\sin(bt)$ is between 1 and -1. So, the range of $h(1 + \sin(bt))$ is:

$$0 < (1 + \sin(bt)) < 2$$

An explicit value is not possible to find due to the non-autonomous nature of the function.

When the value of $H = 563$ (known as bifurcation point) we consider three different values of harvesting:

1. $H = 563$
2. $H > 563$
3. $H < 563$

For $H = 563$, there is only one equilibrium point. Figure 7 shown as below:

![Figure 7. Logistic growth with periodic harvesting, $H = 563$](image)

The effects of the sine function are apparent in the slope field. For initial value larger than 563, the population will decrease and approach 9822. For initial value less than 563, the population will lead to extinction. Table 5 summarize the result.

| Interval       | Sign  | P(t)         | Arrow    |
|----------------|-------|--------------|----------|
| $(-\infty, 9822)$ | Minus | Decreasing   | Point Down |
| $(9822, +\infty)$ | Minus | Decreasing   | Point Down |

For $H > 563$, let $H = 650$. Figure 8 shows that, the population will extinct rapidly for any initial value of the population. There is no stable equilibrium point.
Figure 8. Logistic growth with periodic harvesting, $H = 650$

Table 6 summarizes the result.

| interval | Sign         | P(t)   | Arrow       |
|----------|--------------|--------|-------------|
| $(-\infty, \infty)$ | Minus       | Decreasing | Point Down |

For $H < 563$, set $H = 250$. Figure 9 shows there are two sinusoidal equilibrium points, $P=0$ and $P = 12716$

Figure 9. Logistic growth with periodic harvesting, $H = 250$
For small values of $H$, the function is similar to a standard logistic growth function, with the population collecting around the equilibrium solution $K = 12716$, which represents the carrying capacity. We see that 0 and 12716 are critical points, divide the vertical line into three intervals, which is

1. $-\infty < P < 0$
2. $0 < P < 12716$
3. $12716 < P < +\infty$

Table 7 shows the intervals of equilibrium points that describe whether the equilibrium point is stable or unstable. $P = 0$ is an unstable equilibrium point because the solutions curve more away from this point. When any initial population $P_0$ is less than 0, it is clearly seen that the population extinct. The equilibrium point at $P_0 = 12716$ is a stable equilibrium point because solutions curves are attracted to it. When any initial population taken in the interval $(0, 12716)$, the populations increase to a steady state $12716$. If $P_0$ are greater than 12716, the population declines and approached, a limiting values 12716, which is the carrying capacity.

| Interval          | Sign    | $P(t)$       | Arrow      |
|-------------------|---------|--------------|------------|
| $(-\infty, 0)$    | Minus   | Decreasing   | Point Down |
| $(0, 12716)$      | Plus    | Increasing   | Point Up   |
| $(12716, +\infty)$| Minus   | Decreasing   | Point Down |

4. Conclusion and Recommendations
In this paper, we have obtained the approximate value for the growth rate, $r = 0.17706$ and carrying capacity, $k = 12716$. The effects of different values of the harvesting value on the stability of the equilibrium points has been discussed. With the constant harvesting strategy, the maximum harvesting should not exceed 563. With a periodic harvesting strategy, the maximum harvesting is similar to constant harvesting strategy. In comparing between the two strategies, the periodic harvesting is a better policy. This is because there is a better chance for the squid to reproduce themselves. However, the periodic harvesting is difficult to implement as compared to the constant harvesting because this strategy requires prior information regarding the population level. Therefore, we would recommend the Department of Fisheries to get the exact value by using age-structure method to sustain this actual population of squid.

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