System dynamics modelling of carbon emissions from capture fisheries in West Papua Province

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Abstract. West Papua Province has been planning low-carbon development since September 2022. However, West Papua Province's carbon emissions calculation has not included the fisheries and marine sectors. The number of vessels operating in West Papua continues to increase, and the operation of fishing vessels is one of the most significant contributors to carbon emissions. This study was conducted using a system dynamics methodological approach for modelling and simulating carbon emissions with the Vensim PLE software, especially to generate emission factor values and calculate carbon emissions in West Papua. This study aims to determine carbon emissions, model the operation of fishing vessels to calculate the number of emissions, estimate exhaust emissions from fishing vessels, and classify each fishing vessel into a particular group. Based on historical data, the simulation results are grouped into "business as usual" (BaU), "fair", and "ambitious" scenarios. Based on the BaU scenario, CO_2 emissions show an increasing trend. This is an alarming situation that requires the attention of district/city and provincial governments to establish proactive environmental policies and strategies in low-carbon development planning. In addition, the "fair" and "ambitious" scenarios show that by combining policies limiting fishing fleets that may be operated (Fair: 5000 motorized vessels and 20000 outboard motorized vessels; Ambitious: 4000 motorized vessels and 15000 outboard motorized vessels) and optimizing the hybrid propulsion system (Fair: 15% and Ambitious: 30%) will be able to reduce the carbon footprint significantly. System dynamics modeling can be a powerful and low-cost tool for making low-carbon development decisions.

Key Words: carbon dioxide, greenhouse gasses, model, simulation, system dynamics.

Introduction. Human activities affect the climate and temperature of the earth mainly due to the conversion of forest area and the burning of fossil fuels. A rapid and significant reduction in carbon emissions is needed to limit the impact of climate change and comply with the goals of the Paris Agreement, which is to limit the global average temperature to below 2°C (IPCC 2014).

Capture fishery is a sector that uses high amounts of energy, particularly fossil fuels. The advancement of fishing technology has also led to the motorization of fishing fleets with more powerful engines. It directly increases the demand for fossil fuels. Fuel consumption of fishing fleets is usually the primary cause of increased energy demand and greenhouse gas (GHG) emissions (Parker et al 2018; Kristofersson et al 2021). Therefore, this requires maximum effort in energy efficiency and GHG emission reduction. Energy efficiency will benefit the competitiveness and profitability of fishing households, the capture fisheries industry, and the environment.

Burning fossil fuels for fishing activities will result in the emission of various GHG, including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and non-methane volatile organic compounds. The primary goal of the Paris agreement is to achieve sustainable management of natural resources to reduce GHG emissions and minimize CO_2 emissions from burning fossil fuels (Sala et al 2022). Increasing GHG from capture fisheries activities contributes to global climate change with disastrous long-term implications for the marine environment. Stopping the temperature rise requires action from all parties, including the capture fisheries actors. Taking the right actions in the capture fisheries sector can minimize fuel costs and reduce GHG emissions and damage to marine ecosystems.

The economic sustainability of capture fisheries is highly dependent on fuel consumption. Energy-saving technologies and behavioral changes of the actors will also reduce the damage to aquatic ecosystems, emissions, and fuel costs for capture fisheries. Reducing fishing fleet energy use is critical to achieving sustainable fisheries economically and environmentally. Lower GHG emissions and efficient use of resources have become the political goals of the Indonesian state through the Indonesian Low Carbon Development (LCDI) policy, which is included in the 2020-2024 RPJMN. LCDI is a new development program in Indonesia that aims to maintain economic and social growth through low-carbon emission development and minimize natural resource exploitation. On September 21, 2022, West Papua Province launched a low-carbon development program. However, the calculation of carbon emissions has not yet been integrated into the fisheries sector, including in capture fisheries. Considering all these problems, it can be concluded that it is necessary to know the quantity of GHG emissions when estimating the carbon footprint of fishing fleet activities in West Papua.

This paper aims to quantify the carbon footprint of capture fisheries in West Papua Province by categorizing two emission sources: diesel-fueled and gasoline-powered outboard motor boats, which mostly operate in West Papua. The primary data was obtained from the Fisheries Statistics Data for 2015-2020 (KKP 2022). To estimate the carbon footprint, particularly CO_2 emissions, different scenarios are determined from the system dynamics modelling approach. It is a method for modeling, simulating, and analyzing complex and dynamic systems.

Material and Method. Fishing fleets operating in the West Papua region are generally classified into three types: boats without motors, outboard motorboats (boats), and motorized boats (ships) (KKP 2022). Out of the three types of fleets, only boats and ships have the potential to produce carbon emissions. Thus, in this study, both fleets are counted. The specifications of the boats are a size of 7-15 GT, an operating range of less than 30 miles, and does not have a preservation method. Ships have a medium size of 15-50 GT, with an operating distance of 30-50 miles, with ice preservation, and an operating time of less than or equal to 7 days.

Model formulation. This model uses the addition of boats/ships with a modified logistic growth model approach. The modified logistic differential equation is derived from the Verhulst equation, and the logistic equation is described as:

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) - \frac{N}{d}$$

Where: r - fraction of fishing fleet increase (1 per year); N - units in the fishing fleet; K - desired target or carrying capacity (unit); d - age of use of the fishing fleet (years).

The basic method for calculating exhaust emissions was used (Ministry for the Environment 2022), formulated as follows:

$$E = F\ x\ FF\ x\ EF$$

Note: E - emissions (CO_2 emissions in tons); FF - fishing fleet; F - fuel consumption (L per trip); EF - emission factor (CO_2 g L^{-1}) for diesel and gasoline. The equation was modified and used to calculate total emissions by taking into account the type of vessel (boats and ships), length of operating day (trip) and average fuel usage, increase in the fishing fleet, seasonal effects, and annual accumulation.

The fuel consumption (L) per trip is calculated using the following formula:

$$F = T * Cl * Cy$$

Where: F - fuel; T - number of fishing days; Cl - conversion per trip to L; Cy - day-to-year conversion. The length of the operating days (trip) was calculated using the following formula:

$$T = (ss * st) + (ps * pt) + (ts * tt)$$

Where: T - number of fishing days per year for ships; ss - effect of fishing storm season on ship trips; st - stormy fishing days; ps - effect of peak fishing season on ship trips; pt - peak season fishing days; ts - fishing affected by season transition; tt - transition season fishing days.

Seasonal effects are determined based on the seasons (peak, moderate, and low seasons). The season affects the length of fishing operations (trips). The peak season of fishing usually occurs during the west wind, which is in September, October, November, and early December. During the low season, fishermen usually reduce fishing activities due to frequent strong winds. The seasonal effects are presented in Table 1.

Table 1

Fishing seasons in West Papua

Time of catchment	*Peak season*				*Moderate season*				*Low season*			
Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Windy season	West				Shift 1			East			Shift 2	

Use of system dynamics (SD) models. Gordon (1978) explains that a system is a collection of predetermined rules consisting of elements that interact and are interdependent. Before carrying out the SD approach, the system approach will be transformed into a causal loop diagram (CLD). The CLD is a scientific method that describes the feedback mechanism between one variable and another, showing a causal relationship. CLD is the basis of SD modeling. This is an approach used to describe and model the behavior of complex systems over time. SD models differ from other systems modeling approaches since they use feedback loops, stocks, and flows to illustrate dynamic nonlinear systems (Raharjo et al 2022). SFD are the fundamental components of computer-assisted simulations used in system dynamics modeling (Forrester 1973; Sterman 1989; Richardson 2001; Homer & Hirsch 2006). Figure 1 shows the transformation from CLD to SFD to produce the behavior from the model. Moreover, Forrester (1968) defines SD as a modeling approach to study the feedback behavior of management information systems. It uses models to design system structures and assist decision-making when systems are complex and dynamic.

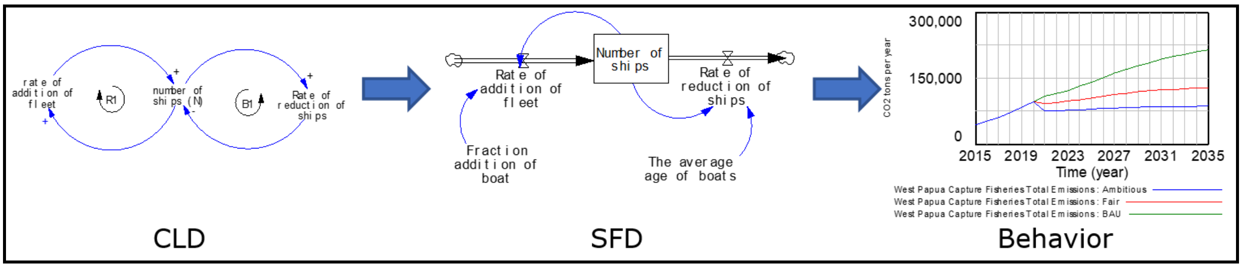

Figure 1. System dynamics modeling approach.

SD was first applied to business management. It is also often used to analyze and assess environmental impacts (Vizayakumar & Mohapatra 1993) of global warming and greenhouse gas emissions (Naill et al 1992; Anand et al 2006; Linton et al 2015; Mamatok et al 2019; Raharjo et al 2022). SD have several benefits, including the capacity to comprehend and assess long-term policies, feedback dynamics, the impact of delays, virtual simulations and experiments, grasping the shortcomings of traditional analytical techniques, and managing complexity and uncertainty (Sterman 1989).

Model validation. Barlas (1996) states that a common problem in addressing this validation is the use of statistical testing with absolute mean error. The statistical test employing absolute mean error verifies the model's output with empirical data by comparing the mean values. It calculates the average value's error percentage (Ei). Model validation was carried out on ships and boat sub-models in west Papua by comparing the average values of historical data and the simulation results. Historical data on the number of ships and boats in 2015-2020 were used to validate the model. The following formula calculates Ei (Barlas 1996):

$$E_i = \frac{|\bar{S}-\bar{A}|}{\bar{A}}$$

$$\bar{S} = \frac{1}{N}\sum_{i=1}^{N} S_i,\ \bar{A} = \frac{1}{N}\sum_{i=1}^{N} A_i$$

Where: A - actual value; S - simulated value; N - time.

Variable determination and data collection. The main variables used in the SD model are listed in Table 2. These variables include exogenous and endogenous variables. Most of the exogenous variables are leverage variables in the model. When a small change is made to an exogenous variable, it will significantly impact the model.

Table 2

Variables of the West Papua capture fisheries carbon footprint model

No	*Variables*	*Initial value*	*Unit*	*Sources/Formula*
1	Ships additional fraction	27	%	Processed data
2	boats additional fraction	18.91	%	Processed data
3	The average age of the ships	12.5	Year	Primary data
4	The average age of boats	17.5	Year	Primary data
5	EF diesel fuel	2689.3	CO_2 g L^{-1}	USEPA (2018)
6	EF gasoline	2347.7	CO_2 g L^{-1}	USEPA (2018)
7	Desired number of ships	5000	Unit	Primary data
8	Desired number of boats	20000	Unit	Primary data
9	Converted day trips of boats	1	day/trip	Primary data
10	Fishing days in low season	3	day/trip	Primary data
11	Fishing days in moderate season	7	day/trip	Primary data
12	Fishing days in peak season	7	day/trip	Primary data
13	The effect of low season on fishing days with ships	4	trip	Primary data
14	The effect of moderate season on fishing days	12	trip	Primary data

No	Variables	Initial value	Unit	Sources/Formula
	with ships			
15	The effect of peak season on fishing days with ships	12	trip	Primary data
16	The effect of low season on fishing days with boats	1	trip	Primary data
17	The effect of moderate season on fishing days with boats	16	trip	Primary data
18	The effect of low season on fishing days with boats	16	trip	Primary data

Policy scenario. To understand the dynamics of the carbon footprint of the capture fisheries sector and as an approach to reducing carbon footprints, the model is simulated using three policy scenarios. Modeling and simulation were carried out using the Vensim PLE software. The policy scenarios are presented in Table 3.

Table 3

Policy scenario for reducing CO_2 emissions in the capture fisheries sector

Scenario	*Limitation of the motorized boat (Unit)*	*Limitation of outboard motorboat (Unit)*	*Optimization of the motorized boat propulsion system (%)*	*Optimization of the outboard motorboat propulsion system (%)*
Business as Usual (BaU)	7500	30000	0	0
Fair	5000	20000	15	15
Ambitious	4000	15000	30	30

The first policy implies the local government's limitation of ships and boats based on the carrying capacity of fish stocks and efforts to reduce emissions. The second policy implies the optimization the boat's propulsion system (hybrid propulsion system). This system improves the efficiency of the main engine by adding an electric propulsion system or new renewable energy.

Results

Causal loop diagrams. The main cause-and-effect diagram (CLD) of carbon emissions from the capture fisheries in West Papua Province is displayed in Figure 2. A closed loop known as the feedback mechanism connects each variable. There are four negative feedback loops (balancing/B) and one positive feedback loop (reinforcing/R). R1 shows that when the fleet variable's addition rate grows, so does the number of ship variables. Nonetheless, the overall number of ships will decline as a result of B1's rate of fishing fleet reduction. B2 illustrates how fewer ships will be produced as carbon emissions increase. B3 illustrates how achieving the targeted aim will result in fewer ships overall by reducing the fleet addition rate and density factor. B4 shows how the fleet addition rate is influenced by the intended goal, which lowers the overall number of ships. B1, B2, B3, and B4 have the opposite overall impact. Sterman (1989) the capacity of system dynamics models to account for feedback loops, which are a feature of complex systems and can be either positive (reinforcing) or negative (balancing) loops, gives them an edge over other modeling techniques. The CLD carbon footprint is presented in Figure 2.

Understanding the cause-and-effect relationship of carbon emissions is also carried out using a causal tree diagram approach. The causal tree diagram explores what variables cause changes directly and indirectly. Thus, this approach is used to configure causal relationships between variables and describe the causes of variables or the reverse direction of causes. Direct changes in emission factors, energy consumption, and the number of ships cause carbon emissions. Carbon emissions are also influenced by indirect variables, namely the number of fishing days, carbon emissions, the rate of addition of the fleet, and the rate of reduction of the fishing fleet. Indirect factors that affect carbon emissions include the number of fishing days, carbon emissions, the rate at which the fishing fleet is added to, and the rate at which it is withdrawn (Figure 3).

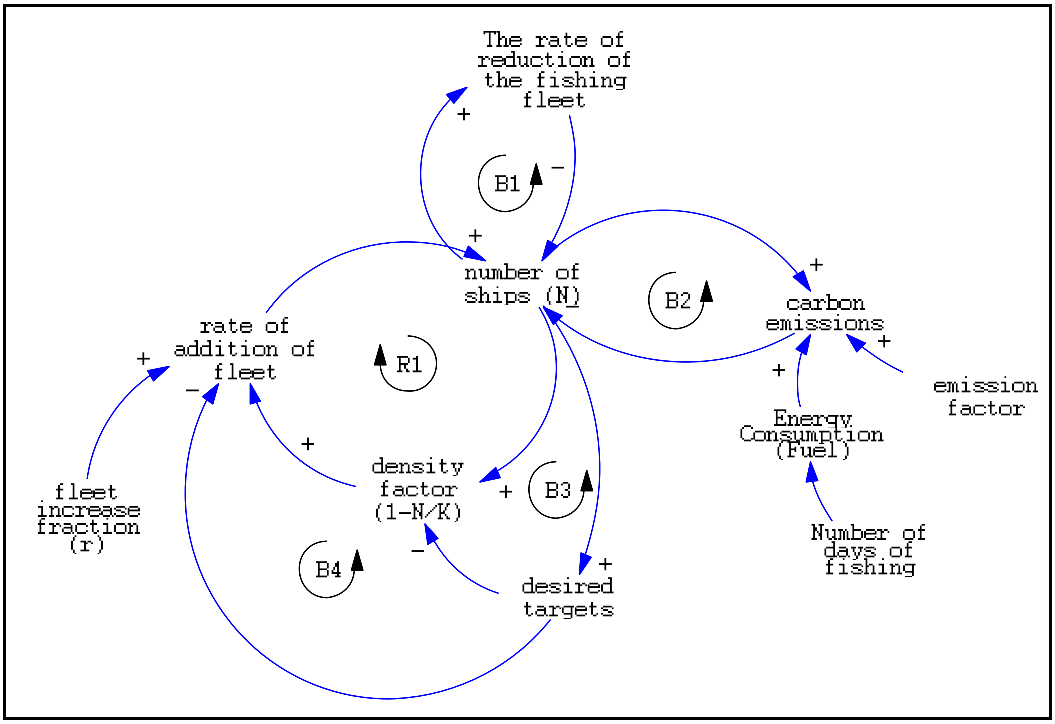

Figure 2. Carbon footprint casual loop diagram of West Papua.

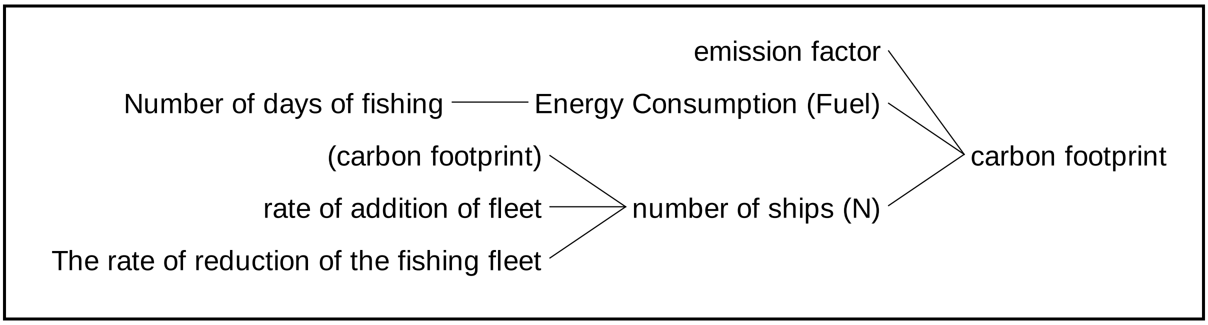

Figure 3. Causes tree diagram of carbon footprint in West Papua.

Stock flow diagram. A stock-flow diagram (SFD) is a transformation of the CLD to simulate the model and generate the phenomenon's behavior. The SFD also discovers the main variables that generate model behavior. This model is based on the logistic growth model and the basic theory of calculating exhaust emissions. It is built into separate sub-models: the number of ships and boats in West Papua and the CO_2 emissions of ships and boats per year (Figures 4 and 5). The model limits are determined based on the logistic growth model (Verhulst model) and the basic theory of calculating exhaust emissions (USEPA 2018). The interlinked sub-models become the total model. A series of variables in the SFD are defined as endogenous (rate, auxiliary) and exogenous (fraction) variables to describe the changing trend.

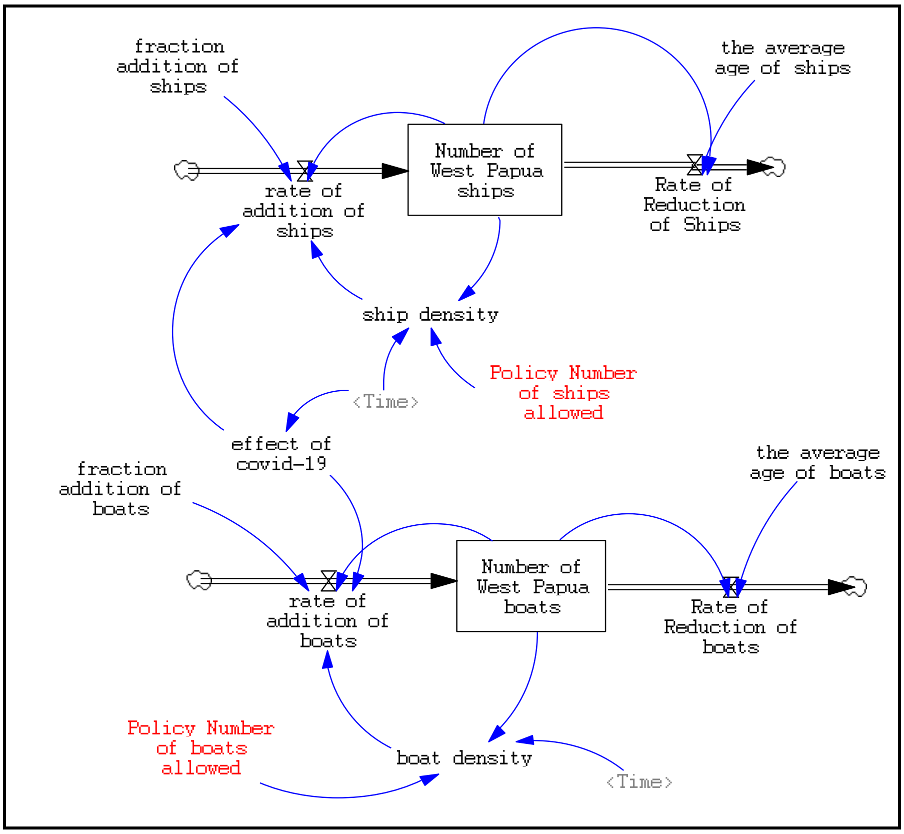

Figure 4. Stock-flow diagram of the number of ships and boats in West Papua.

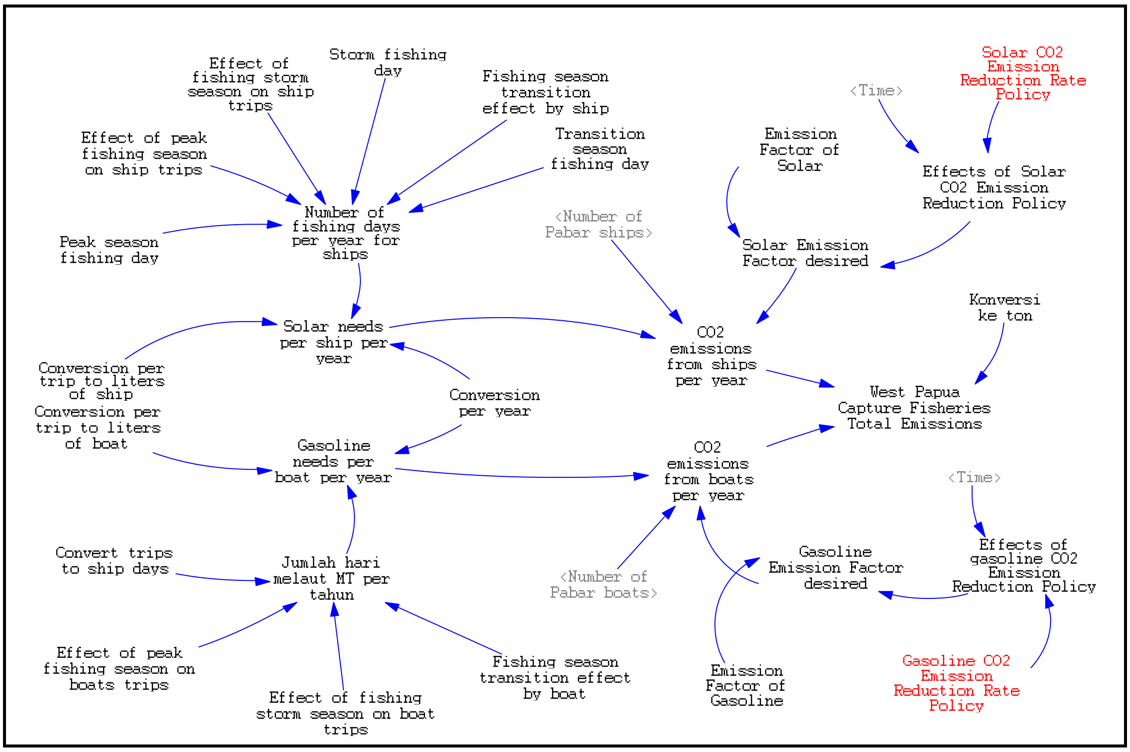

Figure 5. Stock-flow diagram of the total CO_2 emissions in West Papua.

Model validation. The results of calculating the error percentage from the average value (Ei) of the number of motorized boats and outboard motorboats in West Papua are 3.2% and 10.9%, respectively. This means the model can represent the actual addition of ships and boats because the error percentage value is <10% (Figure 6). Muhammadi et al (2001) state that the limit of acceptable deviation is in the range of 5 to 10%.

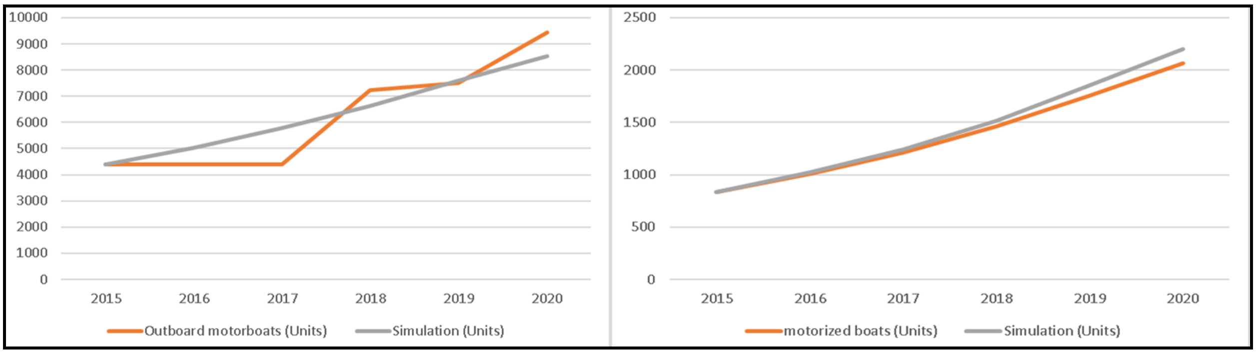

Figure 6. The comparison of historical data and the simulation data.

Simulation results. The results obtained from simulating 21 years (2015–2035) with a time frame of 0.25 dt for the three scenarios are presented in Figures 7, 8, 9, and 10.

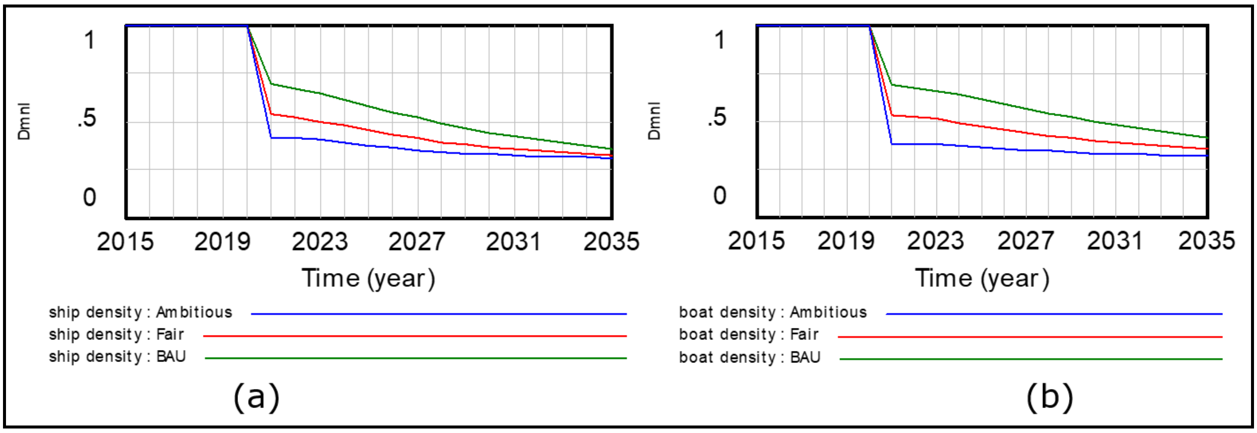

Figure 7. a - the density of ships in the three scenarios; b - the density of boats in the three scenarios.

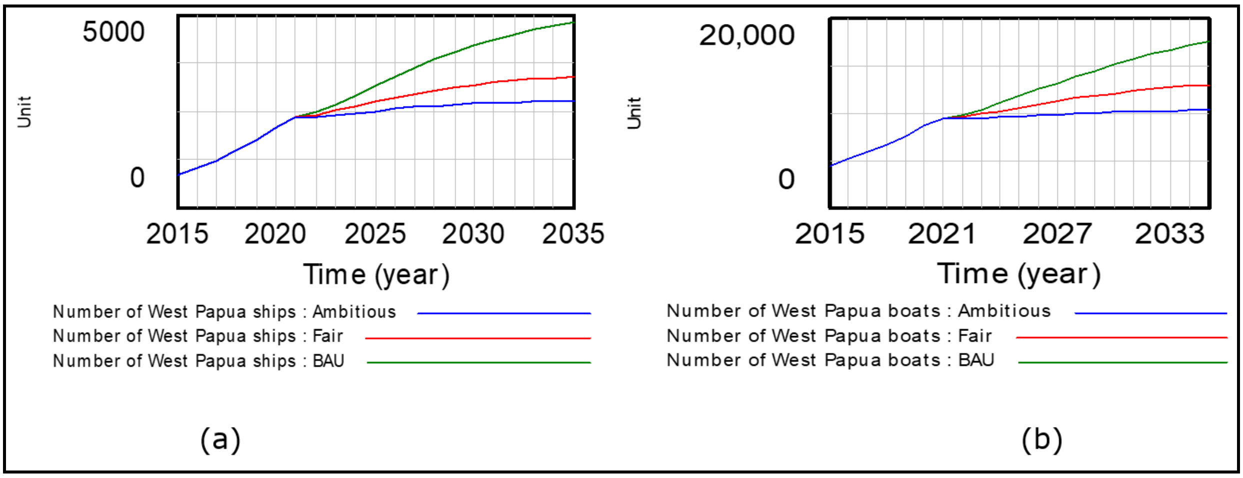

Figure 8. a - number of ships in West Papua; b - number of boats in West Papua.

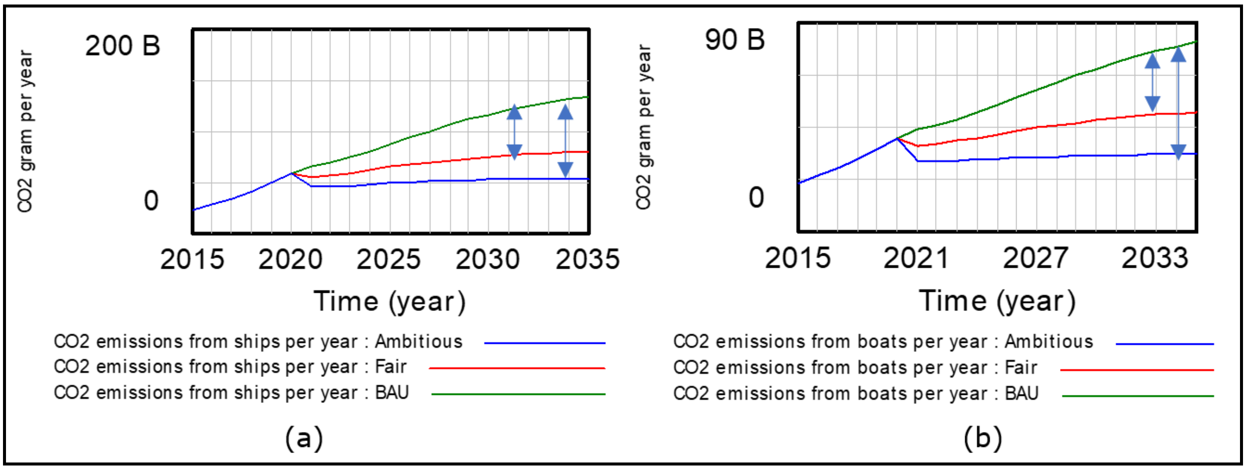

Figure 9. a - CO_2 emission from ships per year; b - CO_2 emission from boats per year.

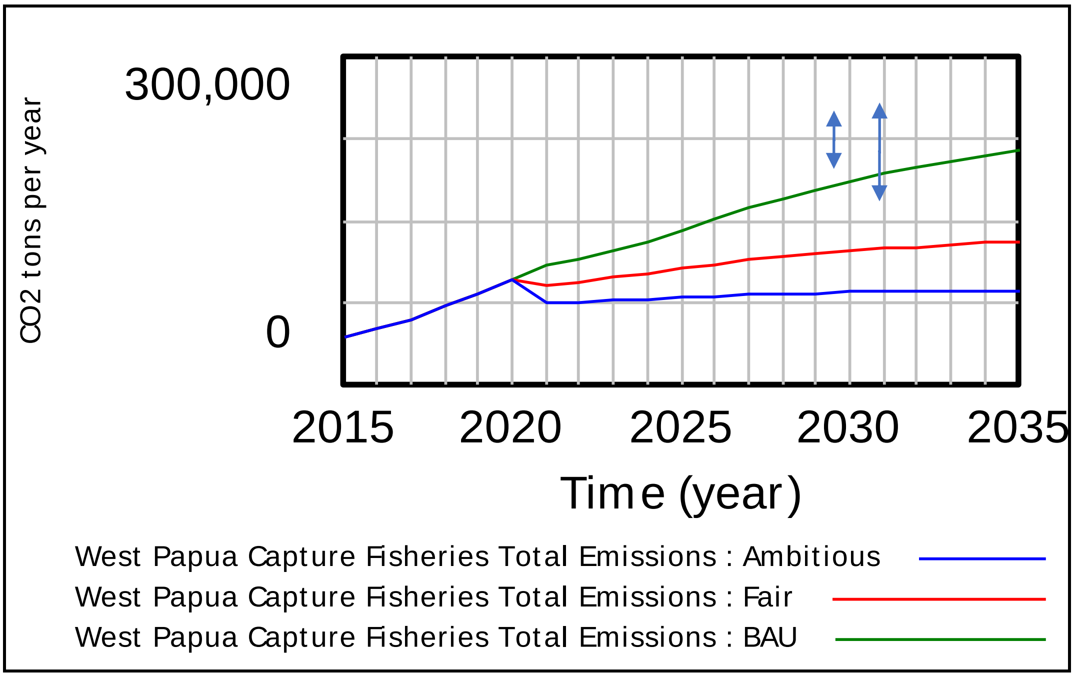

Figure 10. Total capture fisheries emissions in West Papua.

Discussion

Capture fleet density. The increase in the fishing fleet is primarily determined by the maximum fishing fleet that can operate in the ocean and is supported by fish stocks (carrying capacity). Limited fish stocks are a barrier to the operation of fishing fleets. Thus, in building the model, the local government intervention that limits the number of fishing fleets that can operate was considered. The increase in the fishing fleet was assumed to follow the sigmoid behavior (S curve) so that the slowdown in fishing fleet growth is determined by its density (1-N/K). If the density is towards zero, then the fleet growth will experience a slowdown, and if the density is towards one, the fleet growth will accelerate. The density behavior for ships and boats was presented in Figure 7.

Dynamics of fishing fleets in West Papua. The approach to calculating the number of fishing fleets, both motorized boats and outboard motorized boats, is a modification of the logistics growth model by adjusting the fraction of fishing fleet growth, the age of the fishing fleet, and the desired target or carrying capacity as feedback form. This feedback will limit the increase in the fishing fleet (sigmoid behavior). A slowdown in fishing fleet growth will reduce fishing pressure. Policy intervention efforts by regulating the number of fishing fleets would allow the sustainability of the capture fisheries and reduce carbon emissions. This can be seen in Figures 8 and 9, and 10. By implementing this policy, the "fair" and "ambitious" scenarios show an important decrease compared to the BaU scenario.

Figures 8(a) and (b) show that limiting the number of fishing ships allowed to operate starting from 2021 had an important impact. The average reduction in the growth of the number of motorboats is 19.4% when we compare the BaU and "fair" scenarios. In contrast, the delay for "ambitious" vs. BaU was 24.1%. An analysis contrasting the BaU and "fair" scenarios reveals a deceleration in the growth of outboard motorboats with an average increase of 16.1%. In contrast, the slowdown for BaU vs. "ambitious" was 27.2%. Reducing the number of fishing fleets in operation will automatically minimize the carbon emissions.

Carbon footprint of capture fisheries. The SD modeling relates to the main carbon footprint of greenhouse gases produced from burning fossil fuels emitting CO_2 from fishing fleet engines. According to Galli et al (2012), carbon footprint measures the total amount of greenhouse gas emissions, either directly or indirectly, caused by an activity or accumulated during the stages of the production process.

CO_2 is increasing in number or concentration daily and directly proportional with the increasing number of fishing fleets operating at sea. Burning fossil fuels for propulsion engines is one of the main causes of the increase of carbon footprint. Impacts related to climate change due to increased carbon emissions from the fisheries sector will put additional pressures on fish stocks already severely depressed by overfishing.

Figure 9(a) presents the annual CO_2 emissions from motorized boats, while Figure 9(b) presents the annual CO_2 emissions from outboard motor boats. These figures show changes over time in CO_2 emissions, for each scenario and between scenarios. Policy scenario interventions are carried out from 2021-2035, so that the dynamics of reducing CO_2 emissions for motorized boats (the BaU vs. "fair" scenario) averages 31.5%, and the BaU and "ambitious" scenarios average 46.9%. Meanwhile, the dynamics of reducing CO_2 emissions for outboard motor boats (in the BaU vs. "fair" scenario) averaged 28.7%, and in the BaU and "ambitious" scenarios averaged 49%.

Scenarios to optimize the propulsion system of motorized boats and outboard motor boats using a hybrid energy configuration can reduce the carbon footprint of the capture fisheries sector. Inal et al (2022) argue that energy distribution is mainly carried out using an electric system in a hybrid energy configuration. These systems for ships can be classified into three configurations: serial, parallel, and combined serial-parallel. Furthermore, Zahedi et al (2014) stated that a DC system without energy storage provides significant fuel savings compared to a conventional AC system. Optimal energy storage in a DC system results in two-fold fuel savings.

Conclusions. The increase of greenhouse gases from human activities is causing global climate change with disastrous long-term implications for the marine environment. By taking the right action now, the capture fisheries sector can lower fuel costs, reduce greenhouse gas emissions, and reduce the damage they cause to marine ecosystems. In general, the capture fisheries sector contributes to increased carbon emissions and indirectly escalates climate change risk. Policies that regulate the number of fishing fleets and optimize fishing fleet propulsion systems are part of the efforts to adapt to climate change. These policies can tackle the risks of climate change and can play an important role in reducing carbon emissions. Changes in fishing methods can be promoted by removing fossil fuel subsidies, which produce environmental risks. At the same time, the government needs to provide financial and other incentives to reduce the use of fossil fuels. Additional budgets for the capture fisheries sector can be provided to facilitate the change to new equipment and the provision of particular quotas or fishing zones for low-emission fishing fleets.

Conflict of Interest. The authors declare that there is no conflict of interest.

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