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Agriculture System Modeling to Increase Productivity and Production Through Sustainable Resource Management

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Abstract

Mismanagement of soil nutrients, poor site selection of loose soil, steep slopes for agriculture, parallel contour plowing, ground cover removal, and slash-and-burn contribute to soil degradation and erosion. Therefore, developing strategies and policies related to improving productivity, production, and better resource management is important to achieve a sustainable agriculture system. This paper aims to provide an analytical model of the agriculture system to increase productivity and production through sustainable resource management. System dynamics (SD) modeling was used to model the relationships between significant variables in improving land productivity, production, and sustainable resource management. SD can accommodate complexity and nonlinearity in real systems. Increasing resource management is required to achieve a sustainable agriculture system. Better resource management can be done using superior seeds according to location, balanced fertilization, and the application of plant-based pesticides. Productivity depends on water availability, rainfall, temperature, seed quality, the effect of the Jajar Legowo planting system, pest and disease control, soil nutrients, and soil fertility. Rice production is affected by milled rice production, rendement, and lost seeds.

Keywords: agricultural productivity, sustainable resource use, analytical modelling, system dynamics, sustainable production

1. Introduction

Slow growth in agricultural productivity has persisted for nearly three decades. Therefore, a strategy is needed to increase self-sufficiency by increasing its comparative advantage in food crops (Barichello & Patunru, 2009). This strategy refers to established methods for increasing productivity and sustainable resource management through improved resource management, such as better irrigation maintenance, reduced water waste, groundwater depletion, water pollution, and soil degradation.

Java Island is the main rice-growing area, accounting for almost 60% of the total national harvested area (Syuaib, 2016). Java is the most important island for farming activities due to its fertility, and the land is suitable for crop production. Rice is the staple food for more than 80% of the population and the main source of income for farmers. Therefore, rice is an important food crop in Indonesia. Consequently, the application of chemical fertilizers increases dramatically because the government pushes to increase productivity and food self-sufficiency. However, farmers' consumption of fertilizers for crop farming tends to decline due to high fertilizer prices leading to declining purchasing power.

The diversity of productivity, distribution, and consumption among regions in Indonesia is sometimes insufficient. Indonesia still relies on imports to meet domestic needs (Syuaib, 2016). The inefficient use of fertilizers has led to water and soil pollution. Indonesian agriculture has faced the risk of water scarcity, and rice production implies that rice farmers must share water with other domestic users and producers. Mismanagement of soil nutrients and poor site selection of loose soil and steep slopes for agriculture, parallel contour plowing, ground cover removal, and slash-and-burn contribute to soil degradation and erosion. Land degradation most often occurs when farmers are unaware of the dangers of poor site selection. Technically, inappropriate irrigation can also damage the soil. Land productivity is influenced by seed quality, rainfall, temperature, agricultural mechanization, availability of water, pest and disease attacks, soil nutrients, and fertilizer.

(a) Seed quality: superior seeds (Ciherang, IR 64, Cibogo, Kalimas) are varieties with guaranteed quality that have the potential to increase the productivity of irrigated lowland rice (Putra & Ishak, 2015).

(b) Rainfall: rice plants can grow well in areas with hot climates and contain lots of water vapor with an average rainfall of 200 mm/month or more (Surowinoto, 1982).

(c) Temperature: Rice plants generally require a minimum temperature of 11-25 °C for germination, 22-23 °C for flowering, 20-25 °C for seed formation, and hotter temperatures are required for all (Aksi Agraris Kanisius, 1990). Nationally, irrigated rice fields have decreased production by 11.1%/°C, while rainfed rice fields are 14.4%/°C (Yuliawan, 2012).

(d) The application of the Jajar Legowo planting system technology: It provides a long aisle that is more flexible for farmers to maintain without disturbing the plants. The microclimate between plants is improved, and the plant population is increased. Therefore, rice plants have a higher productivity chance if planted with the Jajar Legowo system (Balitbang Kementan, 2013).

(e) Water availability: farmers will plant rice if it is estimated that there is sufficient water in irrigated and rainfed rice fields. The availability of sufficient water is the main requirement for the growth of rice plants. Irrigation conditions affect the rice cropping index (cropping intensity). The average period of rice planting to harvest is four months, so the maximum planting index is three times (which means planting rice three times a year on the same land). Lack of irrigation water causes rice planting not to be simultaneous.

(f) Pest and disease attack: in practice, the use of new seeds often causes new plant pests or diseases. Pests and diseases significantly affect productivity (Siregar, 2007). One factor that affects pest and disease attacks is pesticides (pest control).

(g) Fertilizer: In general, the use of inorganic fertilizers in the short term can fertilize the soil and add nutrients. However, if it is used continuously (in the long term), it has the side effect of leaving residue. Large amounts of residue will erode soil nutrients. Therefore, balanced fertilization between organic and inorganic is needed to maintain soil fertility. Organic fertilizers can be an option for farmers to increase their agricultural productivity but still rely on environmentally friendly elements. To make organic fertilizers, there are abundant materials available around us. However, farmers are generally reluctant to make organic fertilizers and prefer to buy factory-made organic fertilizers for practicality (Rahma, 2014).

(h) Soil nutrient (soil fertility): the availability of soil nutrients affects plant growth and fertilizer requirements. Balanced fertilization based on the concept of “site-specific nutrient management” is the concept of determining fertilizer recommendations. Fertilizers are given to achieve a balanced level of essential nutrient availability in the soil and optimum to (i) increase crop productivity and quality, (ii) increase fertilization efficiency, (iii) increase soil fertility, and (iv) avoid environmental pollution (Kementan, 2007; Liliane & Charles, 2019).

(i) Effect of using mechanical equipment: The level of mechanization has a significant positive impact on the cost, output, income, and return rate of all types of crops. For every 1% increase in mechanization, the yields of all crops, grain crops, and cash crops increase by 1.2151, 1.5941, and 0.4351%, respectively (Peng et al., 2022).

Rainfall has a positive effect on all crops, but rain cannot reduce the adverse effects of temperature (Haque & Khan, 2022). Agricultural system performance can be measured using resources through a structured process to obtain maximum profit (Essuman, Boso, & Annan, 2020). Value chains contribute to resource management, marketing, sales, and other services, to increase the competitiveness of organizations (Straková et al., 2020). Integration between value chains and farmer operations can result in better operational efficiencies that enable farmers to enhance competitiveness (Quiédeville et al., 2018). Value chain analysis contributes to the advancement of competitive advantage for any given product (Ferdous & Ikeda, 2018). The Bayesian approach and deterministic population model can be used to analyze abundance, productivity, and survival (Cave et al., 2010). Modeling the covariance structure data with legume rotation can provide higher productivity and annual yield compared to a continuous barley system (Singh & Jones, 2002).

From these backgrounds, the research question proposed in this study is how to increase land productivity and production by using superior seeds according to location, balanced fertilization, and the application of plant-based pesticides. To answer the research question, system dynamics (SD) modeling was used to model the relationships between significant variables in improving productivity and production through sustainable resource management. SD can accommodate the complexity and nonlinearity in real systems (Forrester, 1999; Sterman, 2000). The data and information used in this study were obtained from BPS (Central Bureau of Statistics), the Ministry of Agriculture of the Republic of Indonesia, the Ministry of Trade of the Republic of Indonesia, and the Jombang District Agriculture Office.

SD can be used to model agricultural systems (Johnson et al., 2008). Agricultural production is determined by the amount of land allocated and the productivity of the land. More productivity and agricultural production will increase the supply of agricultural products. The dynamic stock of agricultural commodities can be calculated by integrating the net inflows and outflows over time. The data can be used to develop mathematical equations and model parameter values (Bastan et al., 2018). After modeling the system, simulation can be carried out using Vensim Simulation software. System dynamic model scenarios can be developed after the model is validated and a valid model is obtained. The system dynamics simulation model can accommodate internal and external variables affecting production and farmers' income (Suryani et al., 2022).

Two important factors in agriculture include the benefits and needs of water so that water saving policy is a big step towards sustainable agricultural development (Bastan et al., 2018). SD is a method that has integrative capabilities to link physical and social system components, an emphasis on stakeholder participation, and the visual appeal of the SD Model. SD has become an effective tool for water resource planning problems worldwide. Causal loop diagrams can describe groundwater management planning in the Tenggeli Desert region, China, and another in the Palouse region, USA (Beall et al., 2011) . Quantitative models can be used to estimate groundwater withdrawal rates useful for regional water planning and management (Dhungel & Fiedler, 2016). Some previous studies have analyzed partial factors, such as the impact of water resources on regional water planning and management to support sustainable agricultural development. Meanwhile, this research applies better resource management using superior seeds according to location, balanced fertilization, and the application of plant-based pesticides in supporting sustainable resource management. It shows the literature gap and contribution of this research.

This research has several contributions to the literature, including a) formulating the relationship between model variables in operational and strategic decision support in agriculture systems, b) representing the development of the model using system dynamics modeling, and c) formulating several alternative policies to support the operational and strategic decision making in agriculture system.

This paper is organized as follows. Section 1 demonstrates an introduction. Section 2 provides model development, which consists of the development of a causal loop diagram (CLD) and the stock and flow diagram (SFD). Section 3 demonstrates model validation. Section 4 describes scenario development and discussion. Section 5 provides the conclusion and future research.

2. Model Development

This section describes the model development, including the causal loop diagram (CLD) and stock and flow diagram (SFD) developments.

2.1 Causal Loop Diagram Development

A causal loop diagram explains the causal relationship between variables in the modeled system. Several stages are required for CLD development, including 1) system understanding, 2) the determination of some significant variables (endogenous and exogenous variables) on the operational and strategic decision in the agriculture system, 3) explaining the relationship between variables in the causal diagram, 4) polarity determination of the destination variable, and 5) feedback loops identification (balancing (B) and reinforcing (R) loops). The selection of model variables is based on a literature review, observations, and expert opinions regarding the agriculture system's operational and strategic decision support. Some of the variables used in the study and in model development were obtained from several related previous studies. Some of these variables are then integrated into a causal loop diagram (CLD). CLD can be used to describe the relationship between several variables that affect the system performance (Suryani et al., 2022). Table 1 shows endogenous and exogenous variables in each sub-model that form the productivity and production in the agriculture system based on several previous research.

Table 1. The endogenous and exogenous variables

Sub-model	Endogenous	Exogenous	References
Land Productivity and Paddy Production	• Seed quality • The application of the Jajar Legowo planting system technology • Availability of water • Pest and disease attack • Fertilizer • Soil nutrient • Effect of using mechanical equipment	• Temperature • Rainfall • Pest and disease effects	Balitbang Kementan, 2013; Kementan, 2007; Liliane & Charles, 2019; Peng et al., 2022; Putra & Ishak, 2015; Surowinoto, 1982; Syaukat, 2011; Yuliawan, 2012
Rice Production	• Land productivity • Harvested Area • Production of grain (Milled Dry Grain) • Rendement • Yield loss rate		Handaka, 2013

CLD of rice cultivation can be seen in Figure 1. Soil nutrient content affects the need for organic fertilizers. The provision of inorganic fertilizers in the short term can increase soil nutrients. Soil nutrient content affects the amount of inorganic fertilizer required. The application of inorganic fertilizers in the long term can leave large amounts of residue that erode soil nutrients. Soil nutrient content affects the amount of inorganic fertilizer required. Land area affects land conversion. The increasing population growth caused many rice fields to be purchased by housing developers. Land conversion affects land area since it will reduce productive land. Climate change causes an increase in temperature and changes in rainfall patterns (Syaukat, 2011). In general, the use of inorganic fertilizers in the short term can indeed fertilize the soil and add nutrients. Still, if it is carried out continuously (in the long term), it has the side effect of leaving residue. Large amounts of residue will erode soil nutrients.

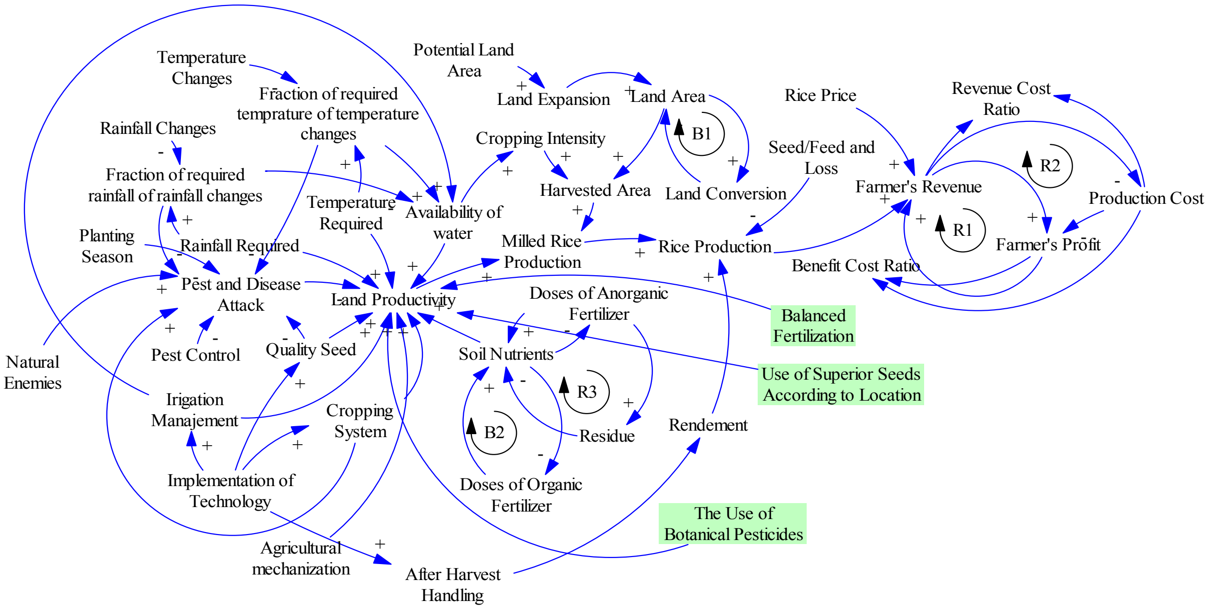

Figure 1. CLD of rice cultivation

The higher the temperature that occurs than the required temperature, the lower the availability of water and the higher the attack of pests and diseases. The higher the rainfall that occurs compared to the required rainfall, the higher the availability of water and the higher the attack of pests and diseases. Factors that affect rice production are land productivity and harvested area. The harvested area is influenced by land area, land conversion, new land clearing, and planting intensity. Factors that affect rice production include unhulled rice production, yield, and yield loss. Yield is influenced by post-harvest handling (Handaka, 2013).

2.2 Stock and Flow Diagram Development

The conceptual model described as a causal loop diagram (CLD) is then converted into a stock and flow diagram (SFD) which provides a bridge to system dynamics modeling. The stock and flow diagram may contain specific symbols and components representing the system structure. Stocks can accumulate flows which represent rates of change that can add to or reduce the stock. SFD has several components, including level (stock), rate (flow), auxiliary, source, and sink (Sterman, 2000). Based on the causal loop diagram in Figure 1, several stock and flow diagrams for agriculture system modeling to support operational and strategic decisions can be developed.

2.2.1 SFD of Land Productivity

SFD of land productivity can be seen in Figure 2. Land productivity is influenced by water availability, rainfall, temperature, seed quality, the effect of Jajar Legowo planting system, pest and disease control, soil nutrients, and soil fertility. The simulation results show that land productivity in the 2000-2018 period tended to increase by an average of 0.6% per year; thus, in 2018, it became 6.75 tons/ha. For 2018-2020 period, productivity tended to decrease by 0.03% per year to 6.07 tons/year in 2021, as shown in Figure 3. This fluctuation in land productivity is caused by seed quality, Jajar Legowo planting system technology, pest and disease control, and rainfall.

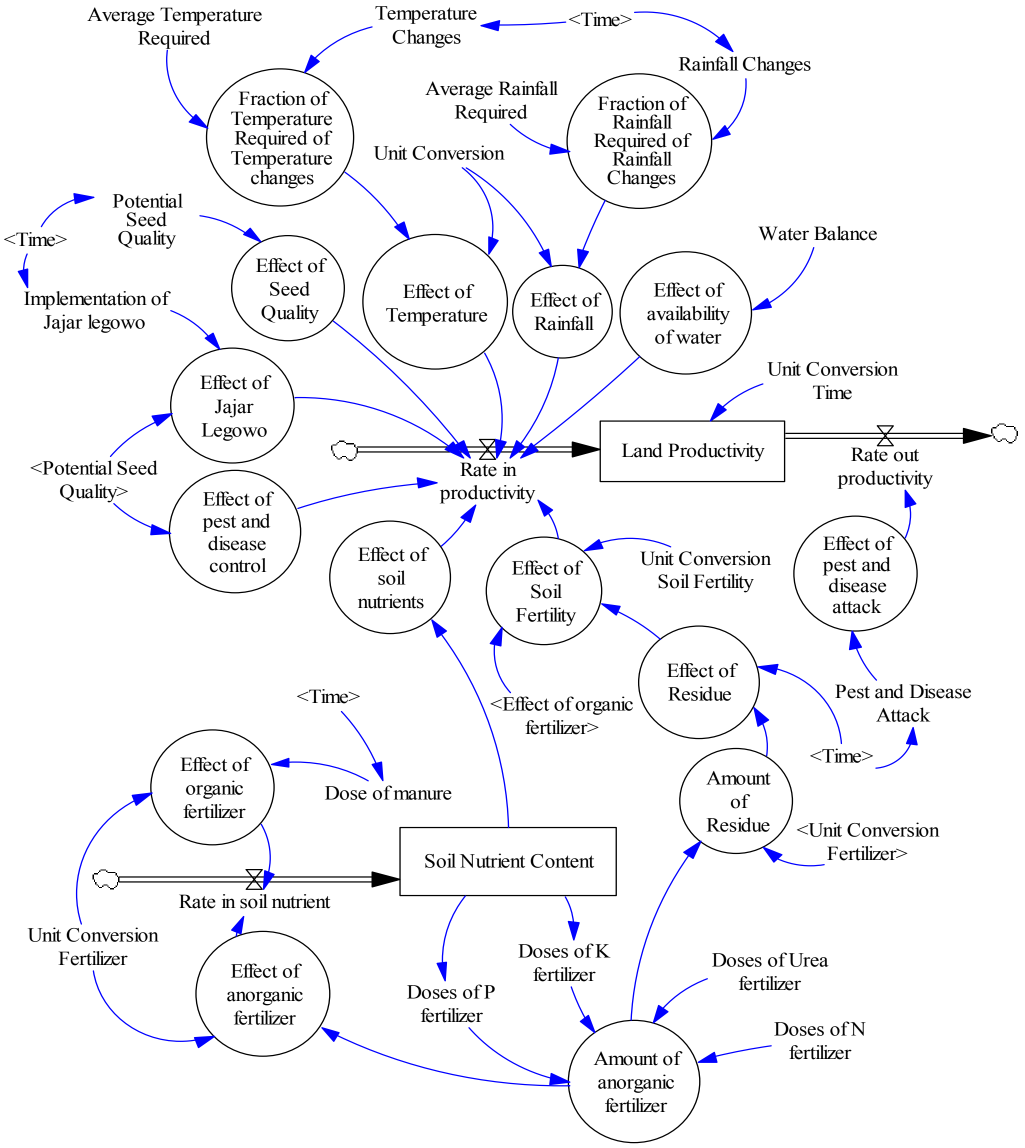

Figure 2. SFD of land productivity

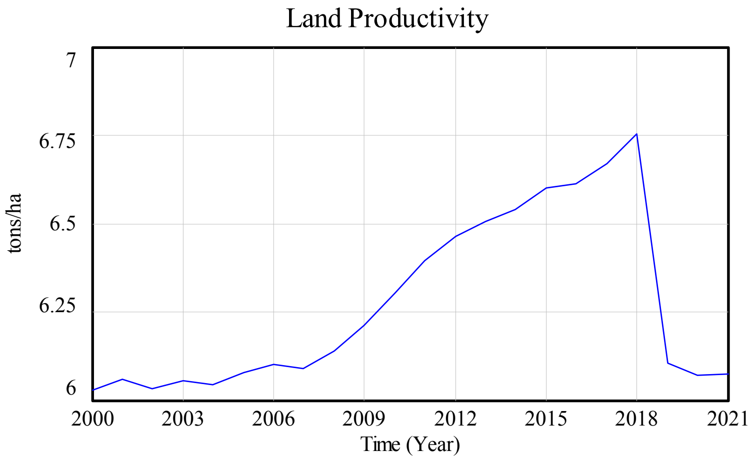

Figure 3. Simulation result of land productivity

2.2.2 SFD of Rice Production

SFD of rice production can be seen in Figure 4. Rice production is determined by milled rice production, yield, and lost seeds. Milled rice production is determined by land productivity and harvested area. Harvested area is determined by cropping intensity and rice land area. The simulation results of rice production fluctuated with a minimum of 11,343 tons and a maximum of 18,257 tons, as shown in Figure 5. Fluctuations in rice production were caused by land productivity and harvested area.

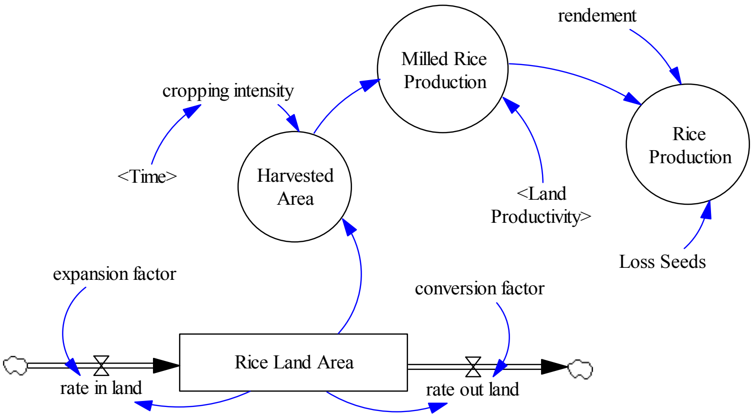

Figure 4. SFD of rice production

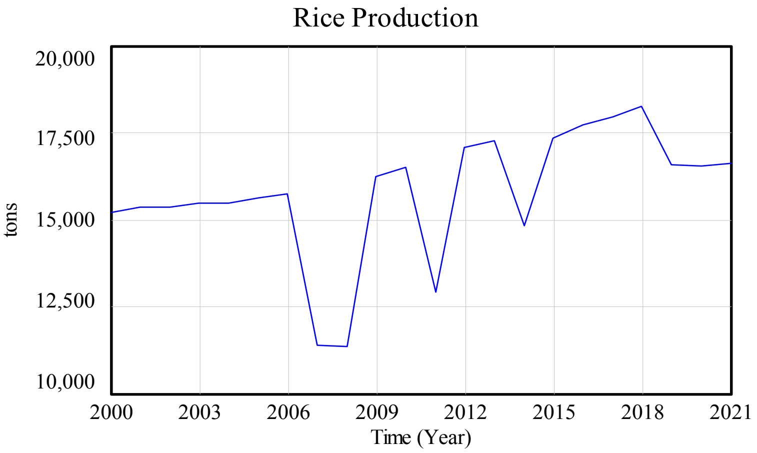

Figure 5. Simulation result of rice production

2.2.3 SFD of Farmer's Profit

SFD of farmer's profit can be seen in Figure 6. The farmer's profit is determined by farmer revenue and total production cost. Meanwhile, the farmer revenue is determined by land productivity and the rice price of the farmer.

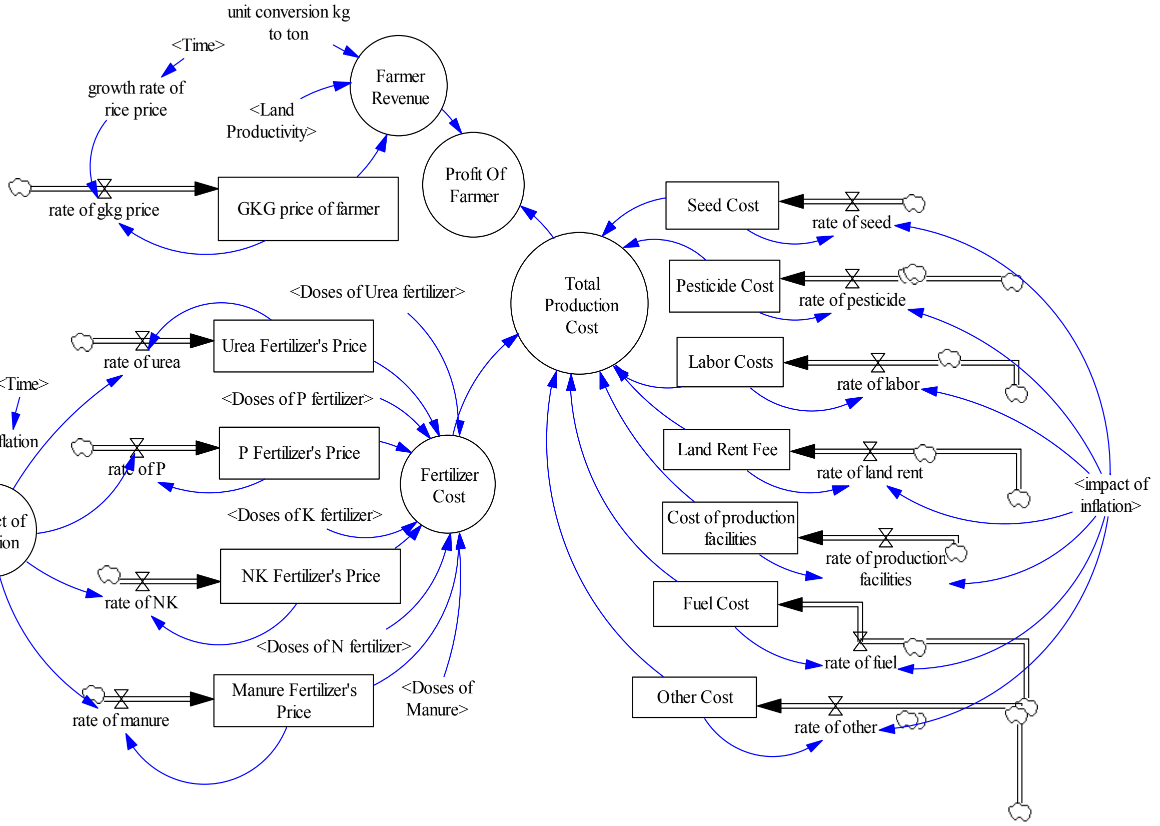

Figure 6. SFD of farmer's profit

The total production cost is determined by the cost of seeds, pesticides, labor, land rent, production facilities, fuel oil, fertilizers, and other costs. The results of the farmer's profit simulation can be seen in Figure 7. The farmer's profit increased in the 2000-2018 period; thus, in 2018, it reached Rp23 million. However, it decreased in 2019 to Rp19.96 million and increased again in 2020-2021 to Rp20.82 million. The fluctuation of farmer revenue causes the fluctuation of farmer's profit.

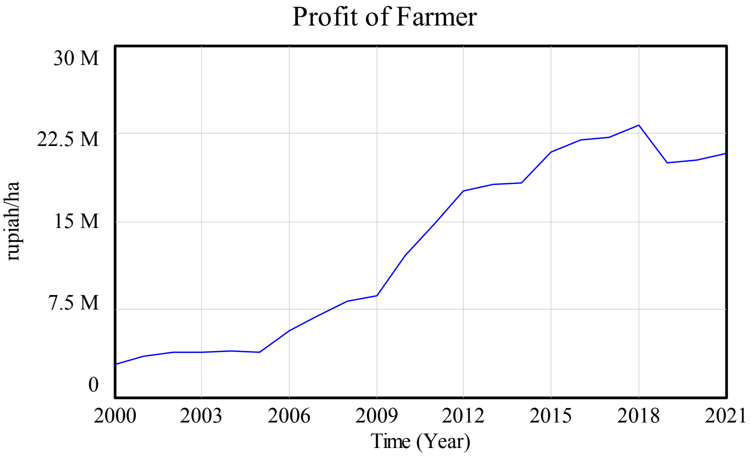

Figure 7. Simulation result of farmer's profit

2.2.4 SFD of Net Revenue of Milling Rice

The net revenue of milling rice is determined by milling machine revenue and operational costs. Operational costs are determined by the cost of packaging, maintenance, transportation, and other costs. Milling machine revenue is determined by the rice price of the rice milling unit and yield. The rice price of a rice milling unit is determined by the average distribution cost, average processing cost, yield, profit margin of the rice milling unit (RMU), mileage, and milled dry grain (GKG) price of the farmer. SFD of net revenue of milling rice can be seen in Figure 8.

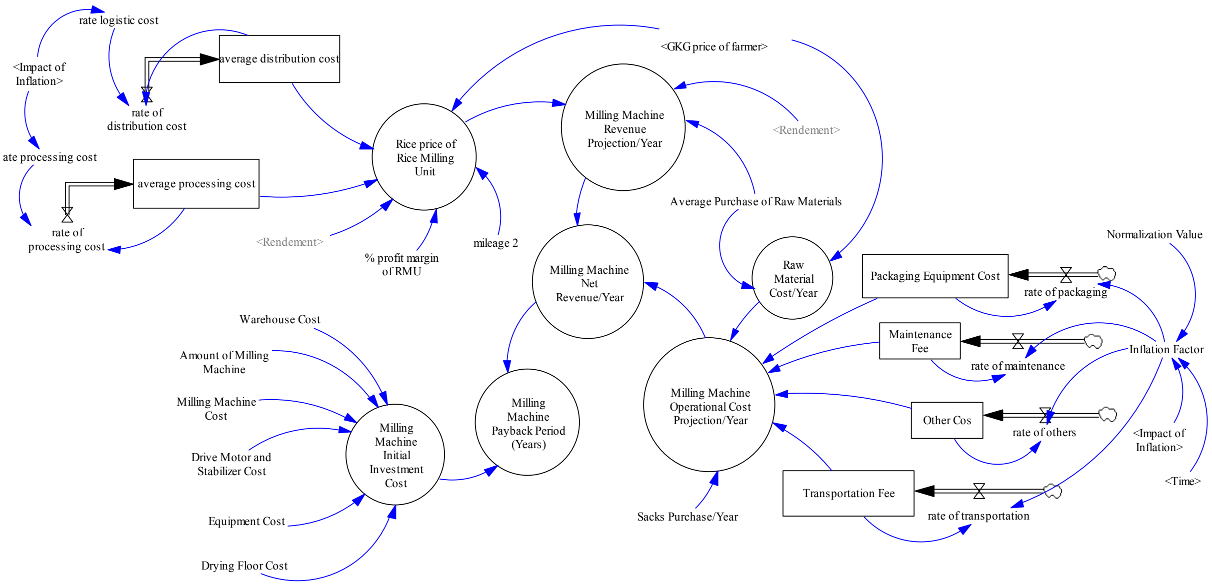

Figure 8. SFD of net revenue of milling rice

The simulation results of the net revenue of milling rice can be seen in Figure 9. Net revenue of milling rice annually fluctuates with a minimum value of Rp124.14 million/year and a maximum of Rp618.03 million/year. This is due to milling machine revenue and operational costs.

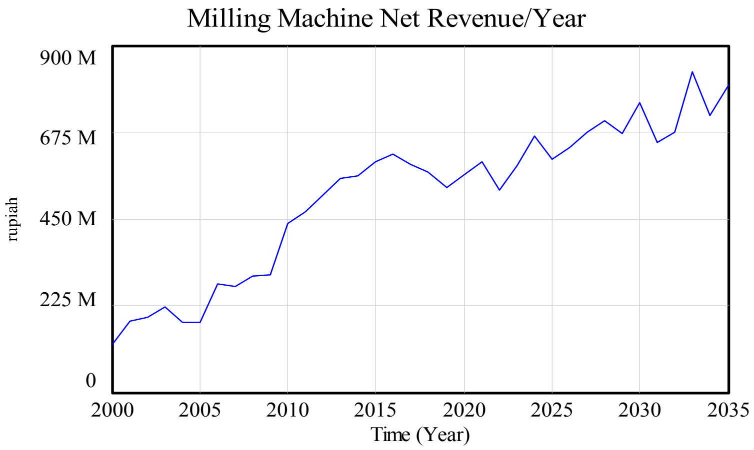

Figure 9. Simulation result of net revenue of milling rice

3.2.5 SFD of Cropping Machine's Net Revenue

Cropping machine's net revenue depends on revenue projection and operating cost, as shown in Figure 10. Cropping machine operating cost depends on the labor fee, the average area of machine rental, the number of workdays, the cropping service machine fee, cropping machine fuel cost, and oil cost. The cropping machine revenue depends on the price and average machine rental area.

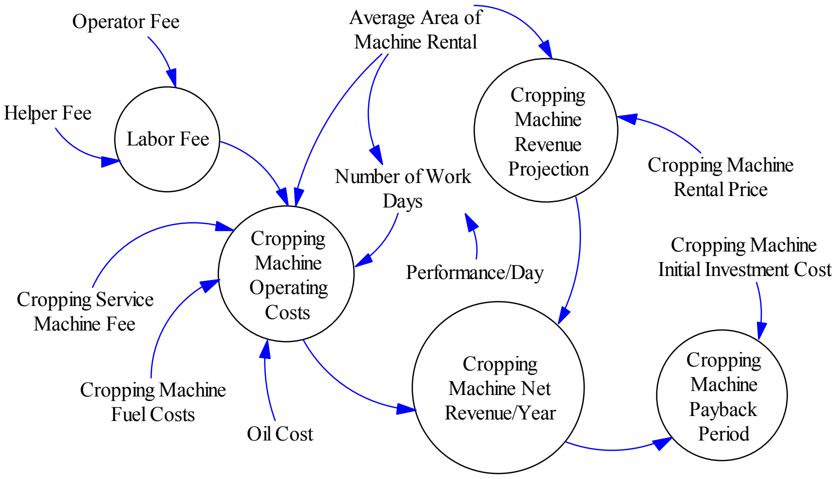

Figure 10. SFD of cropping machine's net revenue

The simulation result of the cropping machine's net revenue can be seen in Figure 11. The cropping machine's net revenue fluctuates with a minimum value of Rp126.57 million per ha and a maximum of Rp252.72 million per ha. This is due to fluctuations in revenue and operating costs.

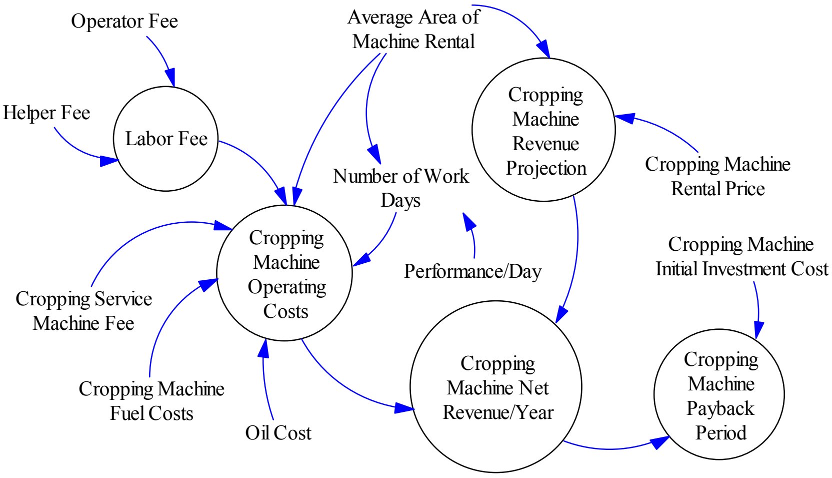

Figure 11. Simulation result of the cropping machine's net revenue

3. Model Validation

Model validation is a process of testing the accuracy of the model through two stages (Barlas, 1989; Qudrat-ullah, 2012), namely: an average comparison test (error rate) and a comparison test of amplitude variation (error variance). The model is categorized as valid if the error rate is 5% and the error variance is 30%. The formulation of the model validation can be seen in Equations (1) and (2).

$$\text{Error rate} = \left|\frac{\bar{S} - \bar{A}}{\bar{A}}\right| \times 100 \quad (1)$$

where, $\bar{S}$: the average rate of the simulation result; $\bar{A}$: the average rate of the data.

$$\text{Error variance} = \left|\frac{S_S - S_a}{S_a}\right| \times 100\% \quad (2)$$

where, S_S: the standard deviation of the simulation result; S_a: the standard deviation of the data.

The error rates and error variances of land productivity, harvested area, milled rice production, and rice (GKG) price of farmer are shown in Table 2.

Table 2. Error rate and error variance of land productivity, harvested area, milled rice production, and rice (GKG) price of farmer

No.	Variable	The Average Rate of Data	The Average Rate of Simulation	Standard Deviation of Data	Standard Deviation of Simulation	Error Rate (%)	Error Variance (%)
1	Land Productivity (tons)	6.32	6.17	0.24	0.22	2.4	10.95
2	Harvested Area (ha)	4,369.74	4,431.73	542.07	466.45	1.42	13.95
3	Milled Rice Production (tons)	27,609.01	27,358.17	3,460.32	3,037.15	0.91	12.23
4	Rice (GKG) Price of Farmer (Rp/Kg)	3,657	3,600	1,671	1,611	1.56	3.58

The results of the error rate and error variance tests for land productivity, harvested area, and milled rice production show all error rates are ≤ 5% and error variances are ≤ 30%. These results indicate that the model developed is valid.

4. Scenario Development and Discussion

Scenario modeling and simulation are useful tools to help formulate challenging decisions in the social, economic, and environmental fields by considering various stakeholders and specific contexts (Awasthi & Omrani, 2018). The scenario of increased productivity using superior seeds according to location, balanced fertilization, and plant-based pesticides can be seen in Figure 12.

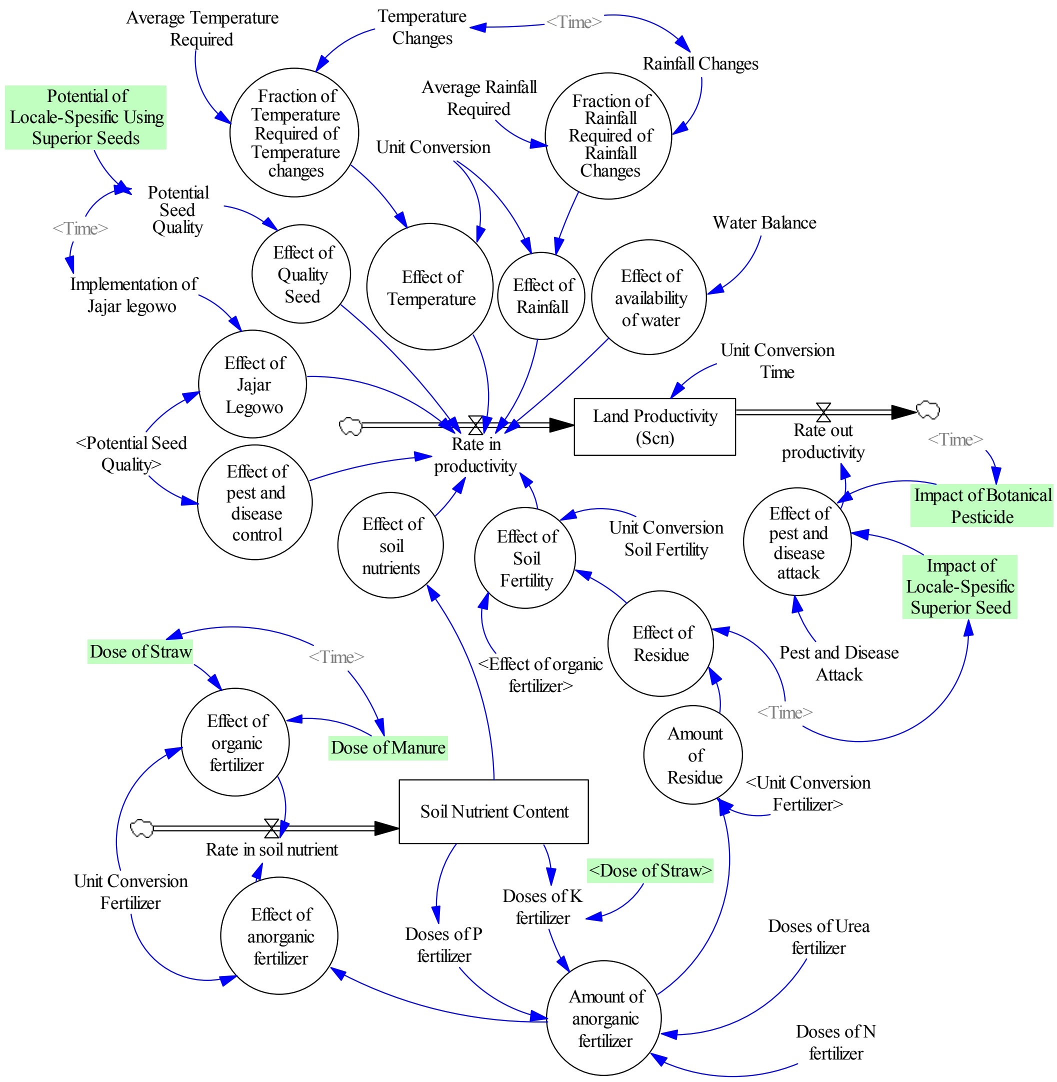

Figure 12. SFD of Scenario of land productivity using superior seeds according to location, balanced fertilization, and the application of plant-based pesticides

Several tools, such as predictive modeling, accuracy evaluation, time series clustering, and structural change detection, can facilitate predictions in building agricultural management information systems (Rupnik et al., 2019). Strategies and policies related to improving productivity, production, and better resource management are required to achieve a sustainable agriculture system. Better resource management can be done using superior seeds according to location, balanced fertilization, and the application of plant-based pesticides.

Using superior seeds suitable for location conditions can reduce pest attacks (see table below) and reduce rice yield losses (Hidayat et al., 2021). In this scenario, we assume the use of the Hipa 12 SBU variety, where it has a potential yield of 10.5 tons/ha in the dry season and 8.9 tons/ha in the rainy season (meaning this variety is drought-resistant).

Its lifespan is also relatively shorter than other varieties, and it is also resistant to several pests, such as moderately resistant to brown planthoppers. The selection of varieties must be adapted to specific locations with the principle of adjusting to the availability of water and pests that often plague the area (Sinar Tani, 2012). The effects of drought and floods affect production yields and variety choices (Prasada, 2022). The use of balanced fertilizers can increase soil nutrients and reduce residues. Fertilization rates must also be based on site-specific (Kementan, 2007). At low productivity levels (< 5 tons/ha), 200 kg/ha urea is required. At moderate productivity levels (5-6 tons/ha), 250-300 kg/ha urea is required. Meanwhile, at high productivity levels (> 6 tons/ha), 300-400 kg/ha of urea is required.

The main problem in rice production is the attack of bedbugs, brown leafhoppers, grasshoppers, ladybugs, aphids, and others. This attack inhibits the growth of rice plants, thereby reducing production or even thwarting the harvest. The application of chemical pesticides can reduce pests and diseases. However, using chemical pesticides in the long term can disrupt the ecosystem. The application of plant-based pesticides can reduce insect populations significantly. The simulation result of scenario of land productivity using superior seeds according to location, balanced fertilization, and the application of plant-based pesticides can be seen in Figure 13. By implementing this scenario, land productivity can be increased from 6.72 tons/ha in 2021 to 7.6 tons/ha in 2035. Rice production tends to increase by 1.3% per year, so that production becomes 20.139 tons in 2035, as seen in Figure 14. Through this scenario, farmers' profits are projected to increase per year by an average of 3.38%, so that in 2035 it is projected to reach Rp. 29.74 million per hectare. Milling rice net revenue per year is also projected to increase per year by an average of 3.83%, so that in 2035 it can reach Rp. 796.74 million. Cropping machine net revenue per year is also projected to increase so that in 2035 it can reach Rp. 250.97 million.

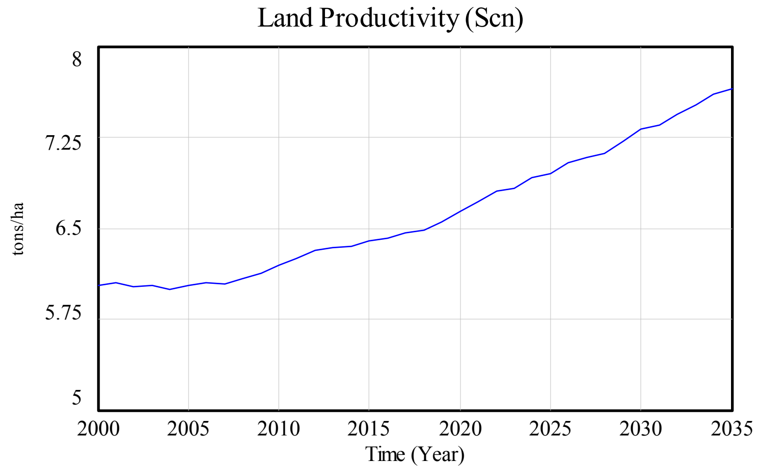

Figure 13. Simulation result of land productivity after using superior seeds according to location, balanced fertilization, and the application of plant-based pesticides

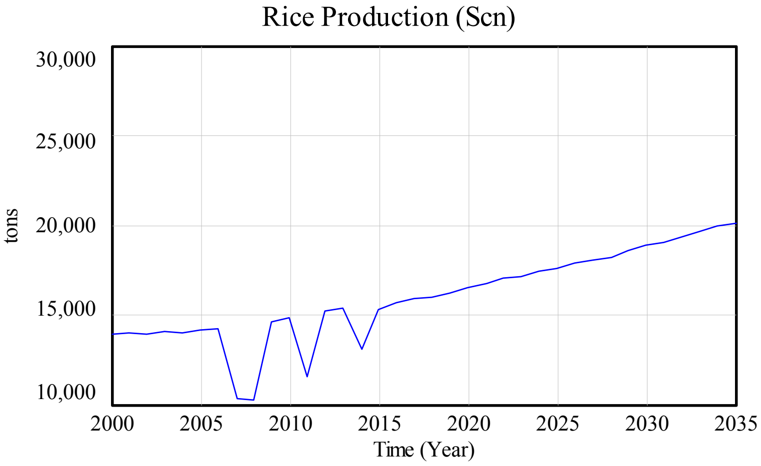

Figure 14. Simulation results of rice production after using superior seeds according to location, balanced fertilization, and the application of plant-based pesticides

5. Conclusion and Further Research

This research addresses rice farming problems under environmental dynamics to increase competitiveness and sustainable resource management. The purpose of this research is to provide an analytical model of the agriculture system to increase productivity and production through sustainable resource management. System dynamics (SD) modeling was used to model the relationships between significant variables in improving land productivity, production, and sustainable resource management as a tool for model development. SD can accommodate complexity and nonlinearity in real systems. System dynamics simulation modeling was utilized to build the model because rice farming problems are complex and nonlinear. System dynamics is proven to model several scenarios to improve system performance. This scenario is carried out by accommodating several variables that can improve rice farming competitiveness and resource management, such as productivity, capital, labor, technology use, irrigation maintenance, and soil degradation mitigation. System dynamics is also proven to predict what will happen in the future by implementing the proposed strategies and policies. Through scenario modeling by changing the structure of the model (adding several system components), projections on future productivity and production can be estimated. The data and information used in this research were obtained from the Central Bureau of Statistics, the Ministry of Agriculture of the Republic of Indonesia, the Ministry of Trade of the Republic of Indonesia, and the Jombang District Agriculture Office. Although the data used in this research are national and regional data from Indonesia and Jombang District, the model's structures and the scenarios were made as generic as possible. They can be implemented in other regions by adjusting the case study's model parameters.

Productivity depends on water availability, rainfall, temperature, seed quality, the effect of the Jajar Legowo planting system, pest and disease control, soil nutrients, and soil fertility. Rice production is affected by milled rice production, rendement, and lost seeds. Milled rice production depends on land productivity and harvested area. Harvested area is determined by cropping intensity and rice land area. Strategies and policies related to improving productivity, production, and better resource management are required to achieve a sustainable agriculture system.

Some of the policy recommendations resulting from this research are conducting better resource management using superior seeds according to location, balanced fertilization, and the application of plant-based pesticides. By implementing this policy strategy, land productivity can be increased from 6.72 tons/ha in 2021 to 7.6 tons/ha in 2035. Rice production tends to increase by 1.3% per year so that production becomes 20.139 tons in 2035. Further research is required to develop scenario modeling to support operational and strategic management in supporting sustainable farming systems. Farmers' profits are projected to increase per year by an average of 3.38%; so, it is projected to reach Rp29.74 million per hectare by 2035. Milling rice net revenue per year is projected to increase per year by an average of 3.83% so it can reach Rp796.74 million by 2035. Cropping machine net revenue per year is projected to increase, so it can reach Rp250.97 million by 2035. Further research is required to create sustainable food systems and support the agribusiness sector through increasing access to markets and promoting inclusive innovation and technology.

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