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Effects of Agricultural Production on Carbon Emissions in Indonesia

Putri Patria Kusuma[1], Sucihatiningsih Dian Wisika Prajanti[2], Amelia Choya Tia Rosalia[3], Bintang Satrio Wibowo[4], Annisa Wulandari, Marsabila Antikasari, Alvito Putra Andi Pradana

[1]First Author's Affiliation: Development Economic, Universitas Negeri Semarang, Indonesia
[2]Second Author's Affiliation: Development Economic, Universitas Negeri Semarang, Indonesia
[3]Third Author's Affiliation: Development Economic, Universitas Negeri Semarang, Indonesia
[4]Fourth Author's Affiliation: Development Economic, Universitas Negeri Semarang, Indonesia

Abstract

Increased carbon dioxide (CO_2) emissions are one of the consequences of activities that have an impact on the environment, including in the agricultural sector. As a country with an agrarian economy, Indonesia faces a major challenge in balancing agricultural production growth and commitment to climate change mitigation. This study aims to investigate the relationship between agricultural production and carbon emissions in Indonesia using 30-year time series data, from 1993 to 2022. The variables analyzed include agricultural land area, fertilizer use, fuel consumption, and agricultural production volume, while carbon dioxide emissions are used as the dependent variable. The analysis method used is multiple linear regression with classical assumption tests to ensure the validity of the model. The estimation results show that agricultural land area and agricultural production have a significant effect on carbon emissions. In particular, it indicates that land expansion tends not to increase carbon emissions, possibly due to lower input intensity extensification-based management. In contrast, agricultural production reflects the impact of intensification and the use of high-carbon inputs in the production system. These findings provide important implications for the formulation of sustainable agricultural policies in Indonesia, emphasizing the need for a transition to an efficient and environmentally friendly low-carbon production system.

Keywords

carbon emissions, agricultural production, intensification, agricultural land

INTRODUCTION

Indonesia is an agrarian country that makes the agricultural sector a key pillar of its national economy. With high food demand coupled with population growth, agricultural production has experienced significant expansion in recent decades. Agricultural land expansion is carried out to increase yields, but this often comes at the expense of forest areas or peatlands that function as natural carbon sinks. This land transformation not only impacts environmental degradation but also contributes to increased carbon dioxide (CO_2) emissions into the atmosphere. Sustainable development has become a guideline for all economic sectors. Finding, solving, and realizing ideal societal conditions is one of the fundamental challenges faced by various countries. Addressing these various problems is certainly inseparable from the process or activities of economic development.

The growth of the agricultural sector in Indonesia has become a crucial pillar of national economic development, particularly in ensuring food security and absorbing labor. However, as agricultural production increases, concerns have also arisen about its environmental impacts, particularly the increase in carbon emissions. Carbon emissions from this sector originate from various sources, ranging from land clearing, the use of fossil fuels for agricultural equipment, to the intensive use of chemical fertilizers. This aligns with the IPCC (2019) findings, which state that the agriculture, forestry, and land-use change (AFOLU) sector contributes approximately 23% of total global greenhouse gas emissions.

One of the main factors influencing carbon emissions from agriculture is agricultural land area. In Indonesia, the conversion of forest land to agricultural land or plantations, particularly for oil palm and rice, contributes significantly to carbon emissions due to the release of carbon from biomass and soil. Agricultural land area is a key indicator in assessing the intensity and scale of agricultural activities. In Indonesia, agricultural land expansion often occurs through the conversion of forest, peat, or other natural land into cultivated areas, particularly for commodities such as rice, oil palm, and corn. This conversion process usually involves biomass burning or peatland drainage, resulting in the release of large amounts of carbon into the atmosphere. Peatlands, for example, store very high carbon stocks and, if drained, release significant CO_2 and CH_4 emissions (Hooijer et al., 2010). A study by Carlson et al. (2013) showed that agricultural land expansion in Kalimantan causes significant carbon emissions from deforestation. Therefore, analyzing the relationship between agricultural land area and carbon emissions is highly relevant to understanding the environmental dimensions of national agricultural production.

In Indonesia, data from Global Forest Watch (2022) shows that agricultural land expansion, particularly for oil palm plantations in Sumatra and Kalimantan, has been a major contributor to the loss of primary forest cover. This increased agricultural land area is closely correlated with carbon emissions from deforestation and forest degradation (Austin et al., 2017). In fact, according to Pendrill et al. (2019), approximately 65% of global consumption-related deforestation is caused by agriculture, and Indonesia is among the three countries with the largest contribution to this consumption-driven deforestation. However, not all agricultural land expansion is automatically detrimental to the climate, depending on the agricultural system used. Agroforestry and sustainable agriculture systems can minimize the impact of emissions. However, land intensification practices without regard for sustainability often exacerbate carbon emissions. Therefore, it is crucial for Indonesia to conduct a spatial evaluation of the impact of agricultural land expansion on carbon emissions as a basis for formulating low-carbon development policies.

In addition to land expansion, agricultural production is also linked to carbon emissions. Modern agricultural production contributes significantly to greenhouse gas emissions, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Activities such as the use of synthetic fertilizers, the burning of fossil fuels for heavy equipment, land cultivation, and land use change are the main contributors to carbon emissions in this sector. Increased agricultural production, especially to meet the growing global demand for food, is often achieved through agricultural intensification and land expansion, both of which have a direct impact on increased carbon emissions. Furthermore, various empirical studies show that increased agricultural production, especially in developing countries, correlates with increased carbon emissions because it relies on external inputs such as chemical fertilizers and pesticides that are energy-intensive. For example, a study by Burney et al. (2010) found that agricultural intensification accounts for about 40% of the increase in global CO_2 emissions since the Green Revolution.

The use of fertilizers, particularly nitrogen fertilizers, also indirectly contributes to increased carbon emissions through the release of nitrous oxide (N_2O), a greenhouse gas more potent than CO_2. Excessive fertilizer use, without regard to sustainable agricultural principles, exacerbates emissions. According to Syahza et al. (2022), the agricultural sector in Indonesia has not fully adopted environmentally friendly practices in fertilizer use, so greater attention is needed in this aspect to reduce the environmental impact of production intensification. Based on this background, this study aims to empirically examine the effects of agricultural land area, agricultural production, fuel consumption, and fertilizer use on carbon emissions in Indonesia.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

Agriculture is a strategic sector for economic development and food security, but it is also a significant contributor to greenhouse gas emissions, particularly carbon dioxide (CO_2), methane

(CH_4), and nitrous oxide (N_2O). A 2021 FAO report indicates that agriculture, forestry, and land use contribute approximately 17–20% of total global emissions. These emissions come from land conversion, biomass burning, chemical fertilizer use, and fuel consumption in agricultural activities. In Indonesia, increasing carbon emissions from this sector require careful attention, given the economy's heavy dependence on agriculture and high population growth.

One important variable in the study of carbon emissions from the agricultural sector is the area of agricultural land. The greater the area of land cleared, especially from forest or peatland areas, the higher the carbon emissions released. Agricultural land is part of the land-use system used directly for the production of food, fiber, and other raw materials. In Indonesia, agricultural land is divided into two main types: rice paddies (irrigated and rain-fed) and dryland (dry fields, fields, and gardens). Agricultural land expansion is often carried out to meet increasing food needs due to population growth and increased demand for export commodities such as palm oil, rubber, and cocoa. Research by Austin et al. (2019) states that the conversion of tropical forest land for agriculture in Indonesia results in significant annual carbon emissions. This is further supported by Hooijer et al. (2010), who confirmed that the draining and burning of peatlands in Sumatra and Kalimantan produces millions of tons of CO_2 annually. This study demonstrates the need for environmentally friendly land-use management in agricultural policy.

However, a major issue is that agricultural land expansion in Indonesia often involves the conversion of natural forests and peatlands, the world's largest carbon sinks. Indonesia's tropical forests store carbon in tree biomass and soil organic matter. When these forests are cleared or burned to make way for agriculture, the carbon stored in the vegetation and soil is released into the atmosphere as CO_2 (Gibbs et al., 2010). This conversion creates a substantial carbon debt that takes decades to hundreds of years to rebalance through carbon reabsorption by vegetation. Peatlands, in particular, play a significant role in carbon emissions due to their high soil organic matter content. When peat is drained for agricultural or plantation purposes, the oxidation and decomposition of the previously water-saturated organic matter generates significant carbon emissions (Hooijer et al., 2010). In Indonesia, areas such as Riau, Jambi, and Central Kalimantan have experienced significant degradation due to the conversion of peatlands to oil palm and rice fields. Emissions from peatland drainage can reach 55–99 tonnes of CO_2 per hectare per year depending on depth and groundwater conditions (Page et al., 2011).

In addition to clearing new land, unsustainable agricultural land management also exacerbates carbon emissions. Practices such as straw burning, intensive tillage (deep tillage), and the lack of crop rotation lead to soil carbon loss and increased land degradation. Agricultural soil that experiences erosion and loss of organic matter becomes a source of carbon emissions and loses its potential to absorb carbon from the atmosphere (Lal, 2020). Another study highlighted that agricultural intensification on existing land is more environmentally friendly than land expansion. This is based on the principle that increasing yields from existing land (with high efficiency) will have a lower emissions impact than clearing new land that releases stored carbon (Searchinger et al., 2018). However, in many parts of Indonesia, intensification is often accompanied by excessive use of fertilizers and pesticides, thus still resulting in high emissions if not managed properly.

In the long term, the clearing and expansion of agricultural land without considering environmental sustainability will contribute to local and global climate change, ecosystem damage, and declining soil fertility. Therefore, agricultural policies must be directed at landscape-based land management, forest and peatland conservation, and incentives for farmers to implement low-emission agriculture. Modern agricultural activities increasingly rely on mechanization and energy-based equipment, such as tractors, harvesters, irrigation pumps, crop dryers, and distribution vehicles. The use of this equipment largely still uses fossil fuels, such as diesel and gasoline, which burn hydrocarbons and release carbon dioxide (CO_2) into the atmosphere. Therefore, fossil energy consumption in the agricultural sector can be considered a direct source of carbon emissions directly related to production activities. A study by Cui et al. (2019) in China reinforces these findings, emphasizing that energy efficiency in agriculture is key to reducing carbon emissions. They found that regions with low agricultural energy efficiency tend to have higher carbon emission intensity. Energy efficiency refers to the ratio of agricultural output to the amount of energy used. In other words, the greater the output generated from a given amount of energy, the lower the carbon emissions per unit of production. Therefore, they suggest transitioning to renewable energy, such as using solar panels for irrigation pumps or biogas from agricultural waste, as an effective emissions reduction strategy.

Furthermore, fuel consumption in this sector is diffuse and hidden (untracked emissions). Unlike large industries recorded in national emissions inventories, smallholder farmers in rural areas use energy on a small scale but in large aggregate quantities. This often results in carbon emissions from the agricultural sector being overlooked or underestimated in national calculations, even though its contribution cannot be ignored. Another problem is the dependence on fossil fuel subsidies in the agricultural sector. The Indonesian government has provided fuel subsidies to farmers in recent decades to support production. However, these subsidies actually encourage the massive use of fossil fuels without considering environmental aspects. A study by Gulati & Narayanan (2020) shows that fuel subsidies in developing countries slow the transition to sustainable agriculture and increase the agricultural sector's carbon footprint. Furthermore, a spatial analysis by Zhou et al. (2021) shows that areas with energy-based agricultural intensification (such as in fertile lowlands or technically irrigated areas) have higher carbon emissions, especially if not accompanied by energy efficiency strategies or energy source diversification. Therefore, a region-specific policy approach is urgently needed to manage energy consumption in this sector.

The use of chemical fertilizers, especially nitrogen fertilizers, produces N_2O emissions, a greenhouse gas with a global warming potential 298 times stronger than CO_2. Excessive and inappropriate fertilizer use leads to leaching and gas emissions from the soil. According to research by Syahza et al. (2022), the majority of farmers in Indonesia use fertilizers without considering environmentally friendly dosages. This aligns with the findings of Reay et al. (2019), who explained that nitrogen fertilizers contribute approximately 45% of total N_2O emissions from the agricultural sector globally. It is also important to examine the relationship between intensive agricultural practices and increased carbon emissions. In many developing countries, agricultural intensification is carried out to meet food demand, but often without regard for sustainability principles. Winiwarter et al. (2018) stated that intensification strategies without proper input management can substantially increase carbon emissions. In Indonesia, the imbalance between productivity and inputs such as fertilizer and fuel remains an unresolved problem.

In general, agricultural production in the context of unsustainable intensification has the potential to increase carbon emissions. Agricultural production that relies on external inputs such as chemical fertilizers, pesticides, and fuel leads to the continuous release of carbon emissions (Zhang et al., 2020). On the other hand, agroecological production and conservation agriculture practices can reduce emissions and increase soil carbon sequestration (Lal, 2020). This suggests that production models significantly determine the direction of the agricultural sector's contribution to climate change. In Indonesia, agricultural production growth is not always accompanied by ecological efficiency. According to data from the Ministry of Agriculture (2022), rice, corn, and palm oil production have increased in the past decade, but this has been accompanied by increased chemical and energy inputs. Research by Nuraini et al. (2018) shows that intensification of rice farming in Java has resulted in increased carbon emissions from soil cultivation, irrigation, and fertilizer application. This strengthens the argument that uncontrolled production increases will enlarge the agricultural sector's carbon footprint.

Several studies also emphasize the need for a spatial approach to examining the relationship between agricultural production and carbon emissions. Research by Boryan et al. (2019) used satellite imagery to measure changes in agricultural land use and correlated them with carbon emission estimates. This approach showed that regions with high production growth have a strong correlation with increasing emissions, particularly in ecologically sensitive tropical regions. Furthermore, the literature indicates that there is a trade-off between agricultural production and carbon emissions, particularly in developing countries that face significant challenges in maintaining food security and environmental sustainability. According to Pingali et al. (2019), the transformation of the global food system must consider the integration of productivity and climate sustainability. Therefore, policies that encourage the adoption of environmentally friendly technologies, incentives for low-emission agriculture, and strict land management are needed..

Several approaches have been taken to reduce carbon emissions from the agricultural sector, including the implementation of conservation agriculture, agroforestry, and precision fertilizer management. Research by Zhang et al. (2020) in Southeast Asia shows that agroforestry can increase productivity while sequestering carbon in soil and biomass. In Indonesia, organic farming practices and efficient irrigation have also begun to be implemented in several regions, although on a limited scale (Ambarwati & Hartono, 2021). From a policy perspective, the Indonesian government has integrated the agricultural sector into the National Medium-Term Development Plan (RPJMN) and the National Energy General Plan (RUEN) to support emission reduction targets. However, implementation on the ground still faces structural and socioeconomic challenges. According to Wibowo & Nuryanto (2022), a gap remains between emission mitigation policies in the agricultural sector and farmers' capacity to adopt low-carbon technologies. Previous studies have largely focused on deforestation and land-use change, but research that simultaneously integrates agricultural land area, population, fuel consumption, and fertilizer use into Indonesia's carbon emissions is still limited. Therefore, a comprehensive study that tests these four variables simultaneously can provide a more complete picture of the dynamics of carbon emissions from the agricultural sector.

HYPOTHESES DEVELOPMENT

Based on previous theoretical and empirical studies, this research develops four main hypotheses:

• First, the greater the extent of agricultural land used, especially from forest or peatland conversion, the higher the resulting carbon emissions.

• Second, increased agricultural production without the adoption of efficiency and low-emission technologies also contributes to the increase in carbon emissions.

• Third, the use of fertilizers, particularly nitrogen, is one of the largest contributors to N_2O emissions from agricultural activities.

• Fourth, the consumption of fossil fuels in agricultural mechanization and transportation directly contributes to CO_2 emissions in this sector.

METHODS

This research is a quantitative study using secondary data sources obtained from the Central Statistics Agency (BPS), the Food and Agriculture Organization (FAO), and the World Bank. The analytical method used in this study is the Ordinary Least Square (OLS) method. Coefficient estimation in OLS can minimize the squared residual value. OLS is a regression method that is later used to determine the least squares value of the regression coefficient. Furthermore, using the OLS method will obtain the smallest residual value, where the lower the residual value, the better the regression analysis results (Rachmadani, 2020 and Sari, 2021). This study will use two to three main variables, so the equation can be written as

$$Yi = \beta 0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + ui \qquad (3.1)$$

Equation (3.1) shows the equation of ordinary least square (OLS), with the information Y is the dependent variable, namely carbon emissions (greenhouse gases), and X is the independent variable, with several types of variables such as agricultural land area, fertilizer use, fossil fuels, and agricultural productivity, and in addition it is a control variable in the study. The control variables include the human development index as an indicator of welfare that can influence a person's production and consumption, per capita income.

Ordinary Least Squares (OLS) is the most common method in linear regression used to estimate the relationship between independent and dependent variables. This technique works by minimizing the sum of the squares of the differences between the actual observed values and the values predicted by the model. In other words, OLS aims to find the best regression line that minimizes prediction error. One of the main assumptions of OLS is linearity, homoscedasticity, the absence of autocorrelation, and normality of residuals. If these assumptions are met, OLS provides a BLUE (Best Linear Unbiased Estimator) estimate, as explained by the Gauss-Markov theorem. According to Gujarati and Porter (2009), OLS is an efficient and unbiased estimation method as long as the classical assumptions of linear regression are met. Furthermore, Greene (2018) emphasized that although OLS is very popular and frequently used in various fields of social science and economics, its weaknesses arise when assumption violations occur, which can lead to biased or inefficient estimation results. Therefore, it is important to conduct classical assumption tests before drawing conclusions from OLS estimation results.

However, the effectiveness of OLS relies heavily on meeting the classical assumptions of linear regression. If any of these assumptions, such as high multicollinearity, heteroscedasticity, or residual autocorrelation, are violated, OLS estimation becomes inefficient and can be misleading in statistical inference. For example, under heteroscedasticity, the error variance is not constant, resulting in biased standard error estimates and invalidating the t-test. To address this issue, researchers typically use the Breusch-Pagan or White tests. If violations are found, alternative approaches such as Generalized Least Squares (GLS) or the use of robust standard errors are recommended. According to Stock and Watson (2020), it is important for researchers to focus not only on the OLS coefficient results but also on ensuring the validity of the underlying assumptions to ensure accurate and relevant model interpretation..

Furthermore, the flexibility of OLS allows for further development in the form of nonlinear regression and other quantitative regression models. For example, the least squares regression approach can be adapted to logistic regression, probit regression, or regression with instrumental variables (IV) when there is potential for endogeneity. This development broadens the scope of OLS to address more complex empirical problems. In the context of economic development, for example, OLS can be used to examine the effect of public investment on regional economic growth by considering regional or time dummy effects.

RESULTS AND DISCUSSION

Before conducting testing, classical assumptions are first processed to examine autocorrelation, multicollinearity, and heteroscedasticity. In linear regression, autocorrelation refers to a condition in which the residuals or errors of a model are correlated with one another, especially in time series data. Autocorrelation can undermine the validity of the model, as the classical assumptions of regression state that errors must be independent. When autocorrelation occurs, it typically indicates that the model has not fully captured the temporal structure of the data. As a result, variance estimates become inaccurate, leading to misleading significance tests. One of the statistical tests commonly used to detect autocorrelation is the Durbin-Watson test and the Breusch-Godfrey LM test (Gujarati & Porter, 2009).

Table 1. Autocorrelation Test

Test	Prob>Chi2	Information

Breusch-Godfrey Serial Correlation LM Test	0.1779	There is no Autocorrelation

Source: processed data, 2025

From tabel 1 we know the test was conducted using the Breusch-Godfrey Serial Correlation LM Test. The test results using the Breusch-Godfrey Serial Correlation LM Test in Table 1 show that the prob>chi2 0.1779 more than alpha 5%. This means model does not include autocorrelation.

Meanwhile, multicollinearity occurs when there is a high linear relationship between independent variables in a regression model. The presence of multicollinearity makes it difficult to estimate the impact of each variable individually on the dependent variable due to information redundancy. Although it does not affect the overall accuracy of the model's predictions, multicollinearity makes the regression coefficients unstable and increases the standard error. To detect multicollinearity, an analysis of the Variance Inflation Factor (VIF) or correlation between variables can be performed. If VIF > 10, then multicollinearity is considered high (Montgomery et al., 2012). The results of the model testing yielded the following results

Table 2. Multicollinearity Test

Variabel	Prob>Chi2	1/VIF
Fuel	5.46	0.183153
Fecom	5.13	0.194788
Lland	4.95	0.202152
LProduction	4.39	0.227972
Mean VIF	4.98	

Source: processed data, 2025

Based on the results of the multicollinearity test shown by the Variance Inflation Factor (VIF) values in the table above, it can be concluded that there are no multicollinearity issues in the regression model. All independent variables have a 1/VIF value above 0.1, or in other words, their VIF values are well below the critical threshold of 10, which is typically used as an indicator of high multicollinearity. Additionally, the Mean VIF value of 4.98 is still within the safe range, indicating that the relationships among the independent variables in the model do not significantly overlap. Therefore, the regression model is suitable for further analysis without concerns about distortion caused by multicollinearity.
Heteroscedasticity is a condition in which the variance of the residuals is not constant across observations. This contradicts the assumption of homoscedasticity, which states that the error has a constant variance. Heteroscedasticity often arises in cross-sectional data containing units with different sizes or characteristics, such as household income or expenditure. When heteroscedasticity occurs, OLS still produces an unbiased estimator, but it is no longer efficient, rendering inference (t-tests and F-tests) invalid. To test for the presence of heteroscedasticity, the White and Breusch-Pagan tests are used (Greene, 2012).

Table 3. Heteroscedasticity Test

Test	Prob>Chi2	Information

Breusch-Pagan	0.4521	There is no heteroskedasticity

Source: processed data, 2025

After conducting the LM test to see whether autocorrelation occurs or not, a heteroscedasticity test is performed. Heteroscedasticity may occur if the residual variance in the model is not constant. Table 3 shows the results of the Breusch-Pagan test, where the prob>chi2 value is greater than alpha 5% at 0.4521 This means that there is no heteroscedasticity in the model.

Based on the explanation of each variable used and the OLS test, several variables were found to influence carbon emissions in Indonesia. Table 4 shows that there are two variables that influence carbon emissions with the equation

Table 4. Regression Result

Variabel	Coefficient	Probabilitas
LLand	-3.3784	0.006
Fuel	-0.0038	0.356
Fecom	-0.0007513	0.335
LProduction	0.609252	0.000
_cons	43.29116	0.011
R-squared	0.9727	
Adjusted R-squared	0.9683	
Prob > F	0.0000	

Source: processed data, 2025

The Effect of Agricultural Land Area on Carbon Emissions

Based on the results in Table 1, it is known that agricultural land area has a negative and significant effect on carbon emissions in Indonesia. This result is evident from the probability value obtained, which is 0.006, which is smaller than the 5% alpha (0.05). This means that the larger the agricultural land area, the lower the carbon emissions produced. This study's findings contradict common narratives that explain land expansion always has a negative impact on the environment. This can occur if the expanded land is used for sustainable cultivation. This finding is supported by research conducted by Andriani et al. (2023), which states that conservative agricultural systems on expanded land can sequester more carbon than they release, primarily through increased vegetation cover. Furthermore, the expanded land is not used haphazardly, but rather for more environmentally friendly forms of agriculture, such as conservation agriculture. In this system, well-cultivated vegetation, whether food crops or cover crops, can sequester more carbon through photosynthesis and the accumulation of above- and belowground biomass.

In agroforestry, farmers plant trees alongside crops or livestock on the same land. This system not only increases long-term productivity but also improves the carbon cycle because trees act as carbon sinks. A study by Andriani et al. (2023) states that land expansion in certain areas can support carbon emission reductions when managed using conservative methods. Furthermore, the expanded land is often previously unused or degraded, such as scrubland or unproductive drylands. Transforming this land into sustainable agriculture can restore its ecological functions, including its ability to store carbon. According to research by Lal (2021), restoring degraded land using conservation agriculture systems significantly increased soil organic carbon content within 3–5 years, thus explaining the decrease in net emissions despite the increase in total agricultural area.

These findings emphasize the importance of distinguishing between “exploitative land expansion” and “restorative or conservative land expansion.” The former typically involves deforestation and leads to a surge in carbon emissions, while the latter can be a climate change mitigation strategy if supported by sustainable land management practices. Therefore, the expansion of agricultural land is not always synonymous with increased emissions, as long as its management is directed towards a system that prioritizes ecological balance.

The Effect of Agricultural Production on Carbon Emissions

Based on the regression results, agricultural production has a positive and significant effect on carbon emissions. This is evident from the probability value of agricultural production or productivity of 0.000 < alpha 0.05, indicating that increased agricultural production is associated with increased carbon emissions. These results indicate that higher production volumes result in greater use of agricultural inputs such as fertilizers, pesticides, and mechanical energy, all of which contribute to greenhouse gas emissions. In this context, agricultural production not only produces food but also has a substantial carbon footprint, particularly in intensive farming systems. In other words, production efficiency does not necessarily lead to environmental efficiency without sustainable input management.

One of the main mechanisms for increasing emissions due to agricultural production is the excessive use of nitrogen fertilizers. These findings align with a study by Sa'adah et al. (2022), which showed that increased production, primarily through fertilizer inputs and crop residue burning, significantly increases CO_2 and N_2O emissions. In addition to fertilizer use, post-harvest crop residue burning is also a major contributor to carbon emissions in the agricultural sector. This practice is commonly used by farmers to quickly clear land, but it releases large amounts of CO_2, methane (CH_4), and N_2O.

Furthermore, numerous field studies have demonstrated that agricultural productivity drives the expansion of post-harvest supply chains, from transportation to processing, which use carbon-based energy. The use of plastic and packaging in the harvesting process also contributes to indirect carbon emissions. This is reinforced by findings by Xu et al. (2020), who stated that the global agricultural system contributes approximately 21–37% of total global GHG emissions, with the largest share coming from intensive production and distribution processes. This demonstrates that increasing agricultural productivity is not an emissions-free process, but rather heavily dependent on high-carbon external inputs. Unless productivity is increased through ecological approaches such as agroecology, organic farming, or precision agriculture, any increase in yield will almost certainly be accompanied by an increase in emissions. Therefore, the regression findings showing a positive and significant relationship between production and carbon emissions are not only logical but also consistent with theory and empirical evidence from various global climate and agriculture studies.

The Effect of Fertilizer Use on Carbon Emissions

The regression results indicate that fertilizer use has no significant effect on carbon emissions. This can be explained by several methodological and ecological possibilities. This insignificance does not mean that fertilizers do not cause emissions, but rather that, in the context and data used, their impact is not strong enough or consistent enough to statistically directly influence carbon emissions.

For example, in field practice, farmers do not always use fertilizers in high or appropriate doses, so their emissions contribution varies and is not consistently measured. For example, farmers in rice fields often use mixed organic fertilizers, manure, or compost, which release emissions more slowly than urea. Furthermore, potential mitigation policies or fertilizer efficiency improvements in the field should also be considered. If technologies such as slow-release fertilizers, biofertilizers, or the jajar legowo (slow-release) planting system, which reduces the need for chemical fertilizers, have been implemented in the study area, the emissions impact could be lower than in areas still using conventional methods. In other words, the insignificance of the fertilizer coefficient may reflect that fertilization practices in that location are environmentally efficient enough not to substantially increase carbon emissions (FAO, 2022).

Considering the various factors described, it can be concluded that the statistical insignificance of fertilizer use on carbon emissions in a model does not necessarily indicate a lack of a true relationship. Rather, it suggests that the effect may depend on the local context, fertilizer type, application method, soil conditions, and interactions with other variables in the farming system.Pengaruh penggunaan bahan bakar terhadap emisi **karbon**

If a regression analysis finds that fuel use has no significant effect on carbon emissions, this result requires in-depth explanation because, theoretically, fossil fuels are a major source of carbon emissions in the agricultural sector. However, this insignificant result can be explained by several reasons and explanations.

First, the amount of fuel used in agricultural practices may be relatively small compared to other emission sources, such as biomass burning, decomposition of organic matter in wetlands, or the use of nitrogen fertilizers. In many traditional agricultural areas, cultivation is still carried out manually or using animal power, resulting in low fuel consumption. In such cases, although fuel theoretically produces carbon dioxide (CO_2) when burned, its contribution to total emissions is not large enough to be significantly detected in statistical models.

Second, data on fuel use in agriculture is often inaccurate or too aggregated, thus not reflecting actual fuel consumption. Farmers may purchase large quantities of fuel, but not all of it is used for agricultural activities—some may be used for household needs, personal transportation, or non-farm activities. In addition, when farmers use more fuel, it may also encourage higher agricultural productivity.

CONCLUSION

The regression results show that carbon emissions from the agricultural sector are differently affected by each component of production input. Agricultural land area has a negative and significant effect, meaning that land expansion managed using a conservative or agroforestry approach can actually help reduce carbon emissions by increasing vegetation cover and soil carbon sequestration capacity. Conversely, agricultural production has a positive and significant effect on emissions, reflecting that increased crop yields tend to be achieved through the intensification of inputs such as fertilizers and fossil fuels, which produce high GHG emissions. However, in this model, fertilizer and fuel use do not show a significant effect on carbon emissions. This insignificance may be due to data limitations, variations in fertilizer types and application methods, and the more dominant role of other factors such as cultivation techniques, energy efficiency, and local emission mitigation policies.

Overall, this model indicates that intensification of agricultural production (through external inputs) plays a significant role in increasing emissions, while sustainably managed land extensification can actually reduce carbon emissions. These findings reinforce the importance of transitioning to a productively efficient yet low-emission agricultural system.

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